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Downtown People Mover (DPM) Winterization Test Demonstration: Otis Elevator

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January 1982
Final Report

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16. Abstract
This report describes the results of the downtown people movers (DPM) winterization test and demonstration program. This program undertaken by Otis Elevator Company - Transportation Technology Division (OTIS-TTD) was conducted during the winter season of 1978-1979 and 1979-1980.

Under this program, test and demonstrations were conducted at the OTIS-TTD test track using typical DPM system hardware under severe winter weather conditions. The capabilities of the OTIS-TTD people mover system to operate reliably within these winter conditions are identified and described.

The OTIS-TTD people mover system with winterization modifications will operate in a normal automatic mode without loss of service during most severe winter weather conditions.

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Winterization, Severe Winter Weather, Manmade Snowmaking, Snow-blower, System Level Test, Snowplow, Snow, Ice, Temperature

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PREFACE

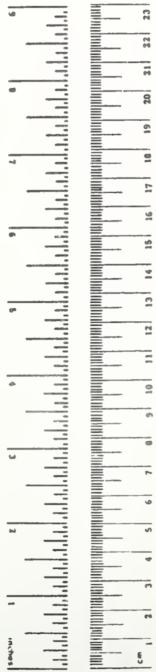
This report was prepared by the Transportation Technology Division of the Otis Elevator Co., Denver, Colorado, under contract DOT-TSC-1584 to the U.S. Department of Transportation's Urban Mass Transportation Administration's (UMTA) Office of Technology Development and Deployment. The contract was managed by the Transportation Systems Center (TSC), Cambridge, MA; Neil G. Patt and Lawrence P. Silva were the technical monitors. The principal Otis participants were Mark Hewitt, test manager and William Womack who served as program manager during the second year of the contract. Mark managed the field activities and development of the test data, and prepared all report documents.

The objective of the program was to demonstrate that fully automated and simple Downtown People Mover (DPM) systems can be a reliable urban transit alternative in severe cold climates. This demonstration was intended to determine the capabilities and limitations of Otis' HOVAIR® People Mover through a combination of subsystem and system-level testing. The testing included evaluation of the system's traction and propulsion, braking and steering, power collection, vehicle and guideway electronics, switching and overall system performance. The test results can be used or extrapolated for quantitative design and performance criteria to be applied by DPM candidate cites in areas of severe winter weather.

METRIC CONVERSION FACTORS

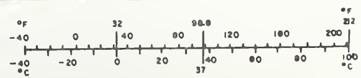
Approximate Conversions to Metric Measures

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



Approximate Conversions from Metric Measures

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



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EXECUTIVE SUMMARY

The Urban Mass Transportation Administration (UMTA) has initiated the Downtown People Movers (DPM) program to demonstrate the viability of automated guideway transit (AGT) in an urban environment. Otis Elevator Co. - Transportation Technology Divisior (OTIS-TTD) was awarded a cost-reimbursable contract (DOT-UT/TSC-1584) to determine the capability of the Otis system to perform under severe winter conditions in a DPM environment. This test program was intended to simulate the operating conditions that a DPM system would be expected to encounter during a typical winter season in the nortern United States.

The winterization project was divided into six tasks, as follow:

Task 1 - Develop a detailed winterization test plan.

Task 2 - Design and specify the test facility.

Task 3 - Procure, assemble, install, and checkout test facility.

Task 4 - Conduct the test program.

Task 5 - Analyze and correlate the test data.

Task 6 - Provide project management.

The project was started in November 1978, and concluded in May 1980. This project used the existing Otis test track which has approximately 2500 feet of guideway configured in a collapsed loop with an offline siding for station stops. The station building has a docking berth, system operational facilities, and a maintenance shop. A 250-foot section of the guideway was designated the winterization test area and modified to enhance winter operation and data collection.

Two vehicles were used during the winter testing program. During the winter of 1978-1979, a vehicle that was built for the Duke University Medical Center (DUMC) was used. The 1979-1980 testing used a test vehicle whose performance was the same as the Duke vehicle. Both are HOVAIR® -supported, linear induction motor (LIM) driven, automated vehicles. The major difference was in the comfort area since the Duke vheicle had HVAC, automatic doors, carpeted floors and quality interiors, while the test vehicle had none of these comfort features.

The snowmaking equipment included snow guns, nozzle stands, and auxiliary equipment such as hoses and valves. The additional equipment required to produce snow included a 2500-gallon water-storage tank, a 6000-gallon-per-hour water pump, a water truck and a large air compressor with an after-cooler.

The meteorological instrumentation measured temperature, relative humidity, barometric pressure, wind speed, wind direction, precipitation type and rate, snow density and accumulations. The ambient temperature proved to be the most significant parameter in determining the number of suitable test days.

A major objective of the project was to conduct performance tests in an environment that simulates the severe winter conditions in the northern U.S. To accomplish this, a test plan was developed prior to the beginning of the test program. The purpose of this plan was to identify the critical system components to be tested and establish the criteria for conducting the tests. The guideway testing started in December 1978, and continued through March 1979. Testing was resumed in December 1979, and completed in March 1980.

The testing included the following situations:

a. Snow and ice removal with normal vehicle operations. These tests demonstrated the ability of the Otis vehicle to operate in a severe winter environment without extensive modifications.

b. Snow and ice removal with test-vehicle snowplow operations. These tests demonstrated the ability to remove large accumulations of snow with an Otis-designed snowplow.

c. Snow and ice removal with maintenance-vehicle operations. These tests demonstrated snow and ice removal by the maintenance vehicle (an 18-hp tractor) equipped with a snow blade and a snowblower.

d. Electrically heating selected components. Before the test program started Otis identified critical components that would require heating to insure operational capability. The effects of resistance wire heating elements were determined for the following components:

   1. Power and Ground Rails
   2. Signal Rails
   3. Emergency Brake Surfaces

e. Other Guideway Subsystems. The testing also evaluated operational capability of the following subsystems:

   1. Continuous Data Communication Antenna
   2. Wayside Sensors

The vehicle tests included exposure to cold temperatures below $0^{\circ}F$. The effects of the low temperatures on vehicle operation and performance were evaluated. These tests included the following:

a. Vehicle Cold Soak Test

b. Effects of Precipitation

c. Vehicle-Mounted Winter Shrouds and Debris Guards

d. Vehicle Power and Signal Collection

e. Vehicle Guidance Switching

f. Vehicle Doors

g. Vehicle Propulsion and Control

The power and signal distribution testing was used to evaluate the ability of the power and signal distribution systems to operate with and without external heat. Additional subsystem test operations included evaluation of the following:

a. Vehicle/Guideway Interface

b. The Lateral Guidance Assembly

c. Test Instrumentation

d. Wind Screens

e. Wayside Control

System-level tests were performed under the following climatological conditions:

a. Baseline system tests, normal temperatures and no precipitation

b. Tests with snow events of less than 15 percent water content

c. Tests with snow events of 15 to 30 percent water content

d. Tests in glaze and rime ice conditions

e. Low temperature tests

The results of the test program have shown that the OTIS-TTD vehicle can be operated in extreme winter climates with little modification to the system. In fact, it has shown that the HOVAIR suspension inherently handles snowfalls of up to 2 inches per hour without any special winter equipment. A snowplow or snowblower is required only when the snowfall is allowed to accumulate for long periods of time.

The test operations clearly indicate that the recommended winter operational scenario for the OTIS-TTD HOVAIR vehicle is to simply continue operations during the severe weather. Even in heavy ice or snowfalls, a debris guard will push the accumulations aside and the system will continue to operate. Because the vehicle is LIM-propelled and, therefore, not dependent on wheel traction for movement, the vehicle can operate over glare-ice accumulations of up to 0.75 inches. The debris guard can handle snow accumulations of approximately 2 inches in depth. For larger accumulations it is necessary to use a maintenance vehicle equipped with a snowplow or snowblower, or the vehicle-mounted plow.

1. INTRODUCTION

The Urban Mass Transportation Administration (UMTA) of the Department of Transportation initiated a program to demonstrate the automatic operation of Downtown People Mover (DPM) systems to provide a reliable urban transit alternative. This report is submitted to UMTA to report the results, conclusions and recommendations of the winter operation capabilities of the Otis Elevator Company, Transportation Technology Division (OTIS-TTD) DPM equipment. OTIS-TTD has operated the winterization test and demonstration project (DOT-UT/TSC-1584) over the last 2 years (1978-79 and 1979-80 winter seasons). This test program is intended to provide a measure of confidence in the OTIS-TTD DPM equipment to perform reliably in severe winter environments.

1.1 BACKGROUND

As automated guideway systems are deployed, assurance must be provided that the systems and their hardware will operate reliably over the range of ambient conditions present in the geographical area of deployment. High system availability will be more difficult to achieve in cities where cold temperatures, snow and ice conditions prevail during the winter season. Candidate DPM systems have not been operated in environments with sufficiently cold-climate weather to provide the level of confidence required for an urban DPM installation. The DPM winterization test and demonstration program provides an evaluation of the OTIS-TTD system under winter conditions representative of northern U.S. cities. Limited winterization testing and evaluations have been performed by Otis Elevator Company and other potential DPM contractors; however, additional winterization testing is necessary to demonstrate the reliable operation of systems and affected hardware under severe winter conditions. The Otis Elevator Company's Denver test track has cold weather of sufficient duration in the winter season to allow evaluation of operations in snow and ice conditions.

1.2 PROGRAM OBJECTIVES

Objectives of the winterization test and demonstration program were to determine the overall system performance in winter conditions, and describe the capabilities and the limitations of the system and hardware including guideway, wayside and vehicular subsystems. Additionally, energy guidelines were to be determined for the removal of snow and ice from the guideway and for the vehicular subsystems to allow normal vehicle operation. Of further interest, the guidelines for the time to restore the OTIS-TTD system to operation after the onset of winter conditions were to be established through this testing program. Specifically, the Otis Elevator Transportation Technology system was to demonstrate the capability of the hardware to operate reliably during winter weather, including cold temperatures, snow accumulations, and icing conditions. As a result of this program, recommendations were to be made for potential system configurations based on winter operations in northern areas of the U.S. Cost guidelines for providing winterization of the OTIS-TTD system also were to be determined.

1.3 SCOPE OF STUDY

The basic purpose of this test and demonstration program was to determine the capabilities or the limitations of the OTIS-TTD system and related hardware, specifically in areas of power collection and distribution, propulsion, braking and guidance, vehicle longitudinal control, vehicle switching, and overall satisfactory system performance during severe winter weather conditions. Additionally, this particular program was to provide hardware requirements for removal of snow and ice accumulations from the vehicle and guideway as necessary to restore system operations after the advent of a severe winter storm event. The program addressed these various areas through a combination of system-level and subsystem testing designed to provide measurements of the capability of the system and associated hardware in various winter climatic conditions. The following task descriptions detail the scope of the work performed as part of the winterization test and demonstration program.

Task 1 - Develop a detailed winterization test plan including procedures and schedules for review and approval by the Transportation Systems Center (TSC). Typical winter weather conditions have been described by UMTA-TSC including temperature ranges, precipitation rates and accumulations, icing conditions, and snow density ranges which accurately represent winter climatic conditions in northern localities of the U.S.

Task 2 - Specify and design the equipment and facilities necessary to demonstrate the system-level operational capability in the winter climatic conditions expected in the northern U.S. The equipment configurations are suitable for engineering tests and evaluation and shall be functionally representative of DPM equipment.

Task 3 - Procure, assemble and install: equipment, hardware, test equipment, and facilities to conduct the test and demonstration program.

Task 4 - Conduct the winterization test program in accordance with the plans, procedures, and schedules developed in Task 1.

Task 5 - Prepare and analyze test results to be included in an evaluation report. Develop a specific delineation of the proposed configurations in hardware and operational philosophies that the test results yield and any modifications to the equipment and hardware that have resulted during the demonstration program. Provide the cost guidelines for the proposed winter modifications to the DPM system and any hardware as might be deployed in locales with winter conditions typical of the northern U.S.

Task 6 - Provide program management for the winterization test and demonstration project, including participation in UMTA/TSC review meetings, the submittal of narrative progress reports based on a formal monthly progress report update, and informal updates of project progress as required. As an emphasis to the work tasks which comprise the scope of the project, include an an identification of those subsystems and components which are most critical to the dependable operation of the DPM system in severe winter conditions. Emphasize and specifically address these critical items by test sequences and procedures to determine the effects of the adverse weather and to specifically define proposed solutions to problems encountered.

2. DESCRIPTION OF TEST FACILITY

OTIS-TTD utilized the Denver test facility for the conduct and operation of the winterization test and demonstration program. The test facility provided the unique flexibility of not only demonstrating vehicle operations from a manual to an automated system level, but of also allowing modifications in or changes to vehicular and guideway hardware as solutions to problems encountered in the winterization program.

2.1 TEST TRACK

The OTIS-TTD test track is comprised of approximately 2500 feet of guideway configured in a collapsed loop with an additional offline siding and representative station. The station building contains the test-track operational facilities and a vehicle maintenance shop. The test-track layout and configuration are shown in Figures 2-1 and 2-2. This test track consists of an at-grade concrete guideway with steel guidance curbs. The concrete guideway is bisected by the installation of the OTIS-TTD LIM propulsion system secondary reaction rail, i.e., the reacted portion of the vehicle propulsion. On either side of the reaction rail are located the vehicle air-suspension flying surfaces, approximately 24 inches in width. On the outboard edge of each flying surface is a sandblast-textured area approximately 6 inches in width for the vehicle emergency braking system. Power distribution to the vehicle is provided by three distribution rails supported by stanchion posts at 7.5-foot intervals. The test-track guideway design is one of a partially-open parapet wall permitting the ejection of some snow from the guideway area. A winterization test area approximately 250 feet in length has been located on the north lane of the Otis Elevator test-facility guideway. This test area includes the addition of guideware hardware to the north side, representative of the Duke University system guideway and potential DPM deployments. Guideway heating was provided for the power distribution rails, and shrouding by a plastic insulative

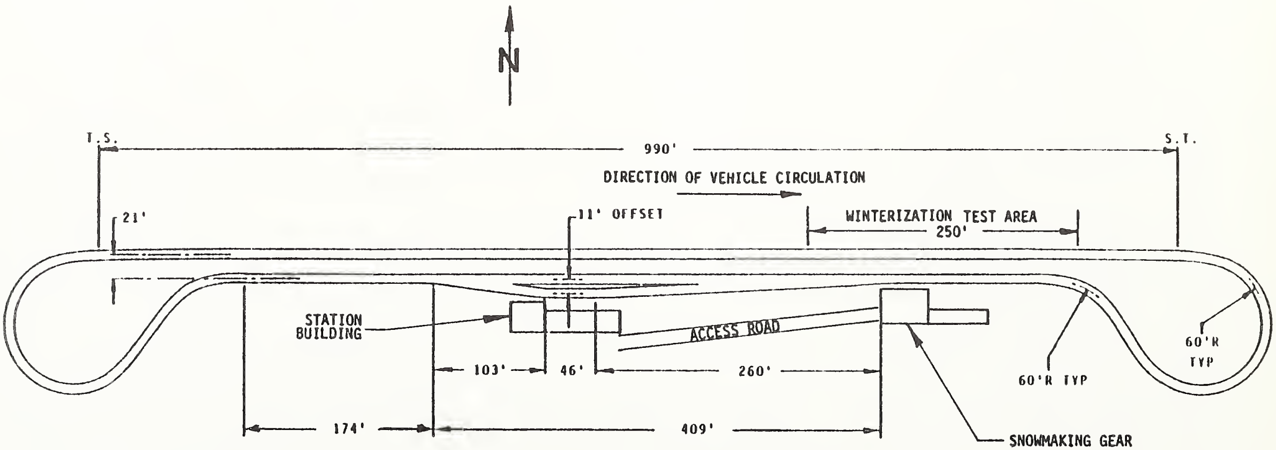


FIGURE 2-1. TEST-TRACK LAYOUT

VIEW OF OTIS TEST TRACK LOOKING WEST

OTIS TEST TRACK WITH SNOWMAKING IN PROGRESS

FIGURE 2-2. OTIS TEST TRACK

cover was provided for the non-contacting surfaces of the rails. Heating was also supplied to the concrete surface in the area of vehicle brake/skid contact to assure the integrity of the emergency braking system during snow and ice accumulations. The test area was also provided with an installation of guidance/ground rail, representative of the Duke University system signal rail and continuous communications antenna. The ground rail and signal rail were also provided with heating to maintain a reliable signal block contact with the vehicle. Tests and demonstrations were conducted in this area of the test track by circulating the vehicle through this area under varying types and levels of climatic conditions. Figure 2-3 shows the OTIS-TTD winterization test area.

2.2 TEST VEHICLE

OTIS-TTD used two existing Otis test vehicles that are most similar to a DPM performance. One was a vehicle that is currently in use at Duke University Medical Center in Durham, North Carolina. The second vehicle used Duke-type hardware, but it did not include some comfort features.

Each vehicle consists of a chassis containing the operating components of the vehicle including the propulsion, suspension, lateral guidance, switching, power collection, and emergency braking subsystems (Figure 2-4). The Duke body includes normal passenger loading of 22 persons and seating for 4 persons (Figure 2-5). The body has biparting doors on either side and ample width to allow easy loading and unloading to cargo and equipment, including standard hospital beds. The body includes emergency-exit provisions through the hinged-glass windows in the ends of the body, which allow passengers to egress onto the guideway. Heating, air conditioning and ventilation are provided within the body to maintain a comfort zone for the passengers; additionally, emergency ventilation is provided during those periods when power is not available for the vehicle. Normal lighting and emergency lighting levels are also provided within the vehicle and in the

WINTERIZATION TEST AREA LOOKING EAST,
SHOWING DPM GUIDEWAY HARDWARE ON LEFT

WINTERIZATION TEST AREA AT NIGHT LOOKING WEST

FIGURE 2-3. WINTERIZATION TEST AREA

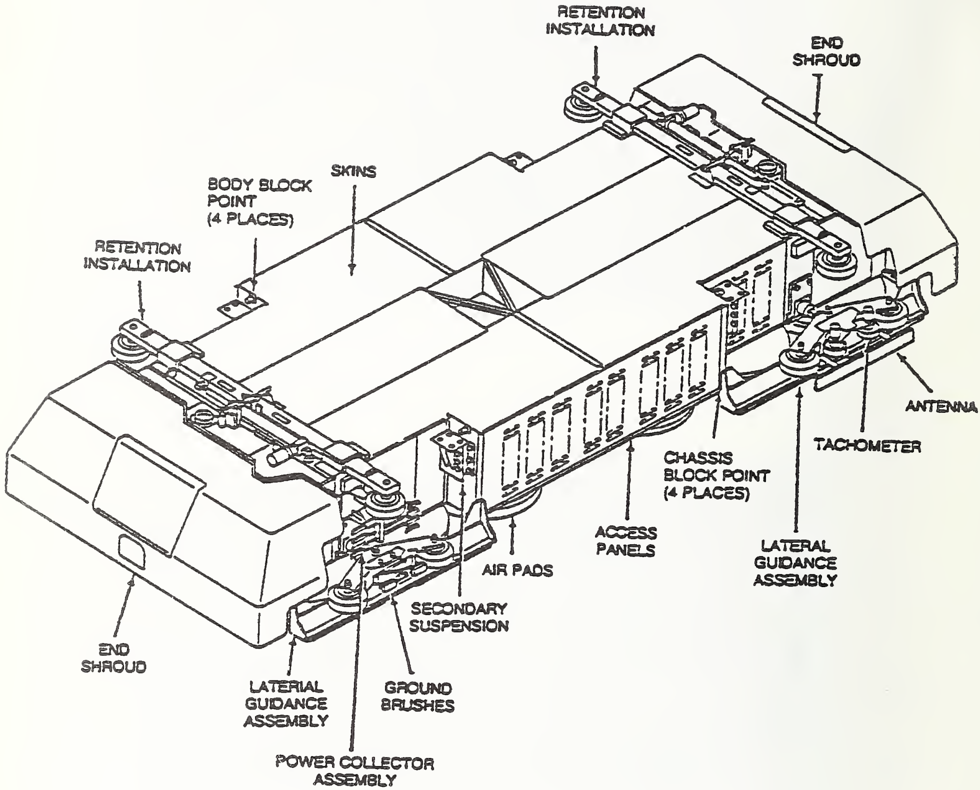


FIGURE 2-4. DUKE VEHICLE CHASSIS ASSEMBLY

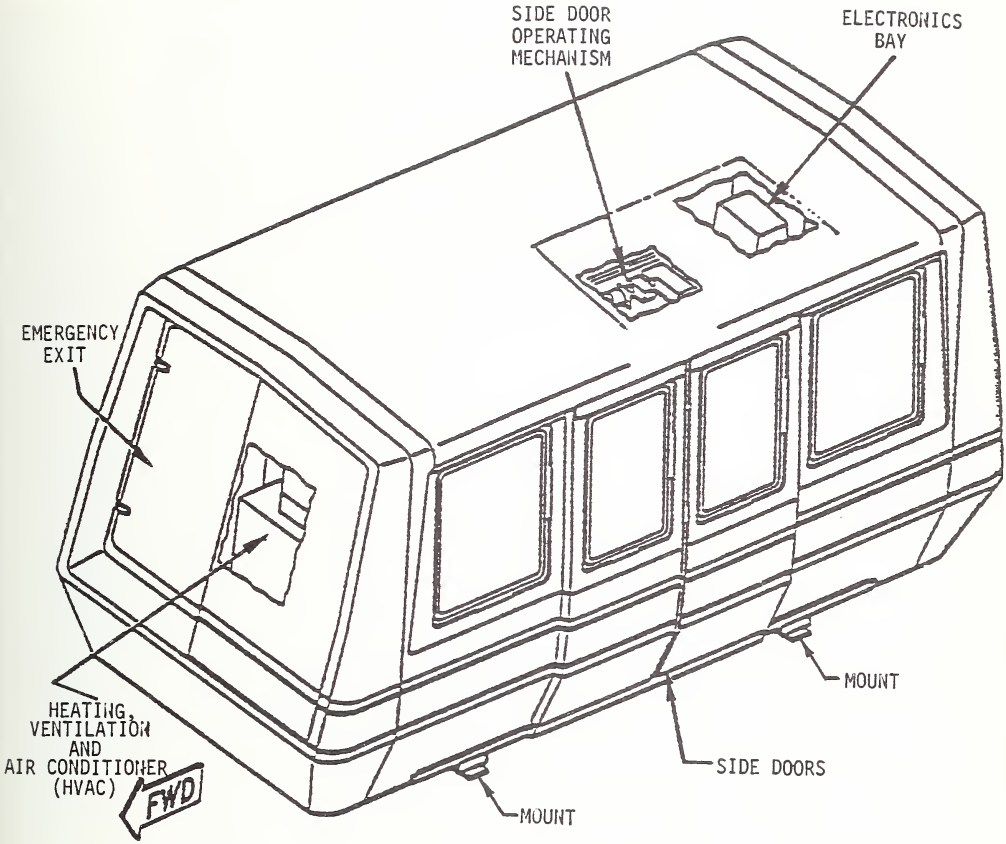


FIGURE 2-5. DUKE VEHICLE BODY

emergency-exit areas. The body also contains the electronic control systems which are housed in a cabinet in the end of the vehicle. The vehicle door operators are located in the ceiling-panel area on either side of the vehicle to provide on-board control of vehicle doors. These vehicle doors are normally operated automatically but for test purposes were operated manually from on board the vehicle. During the winter season of 1978-79, a Duke production vehicle was undergoing final test and checkout at the Denver test track prior to shipment to the customer. This vehicle was used for the winterization system operations for that season which included the test and evaluation and demonstration of all associated vehicle hardware and subsystems, particularly those critically affected by severe winter weather. (See Figures 2-6 and 2-7.) During the winter season of 1979-80, OTIS-TTD developed a test vehicle for use in that year's testing.

The test experiences utilizing the Duke vehicle in 1978-79 indicated no critical problem areas existed with the operation of the Duke body and related hardware subsystems in cold temperatures or winter precipitation. Therefore, the test vehicle deployed in 1979-80 included a "test only cab" used to house and protect personnel and instrumentation on board the vehicle. The test vehicle chassis was the same chassis configuration as used in the Duke production vehicles. This combination of Duke chassis and test body was operated throughout the second winter season for all tests and demonstrations. (See Figure 2-8.) Slight differences in vehicle guideway interfaces between the Duke University system and the test track required that both of these test vehicles be provided with special test-track adaptors for retention and lateral suspension guidance on one side of the vehicle chassis (Figure 2-9), but normal power-collection hardware was retained.

The other side of the vehicle contained the production lateral suspension and guidance, signal collection, grounding, and communications interfaces as specifically found at Duke University in the OTIS-TTD People Mover System (Figure 2-10). Because of the mechanical limitations imposed by the test-track adaptors,

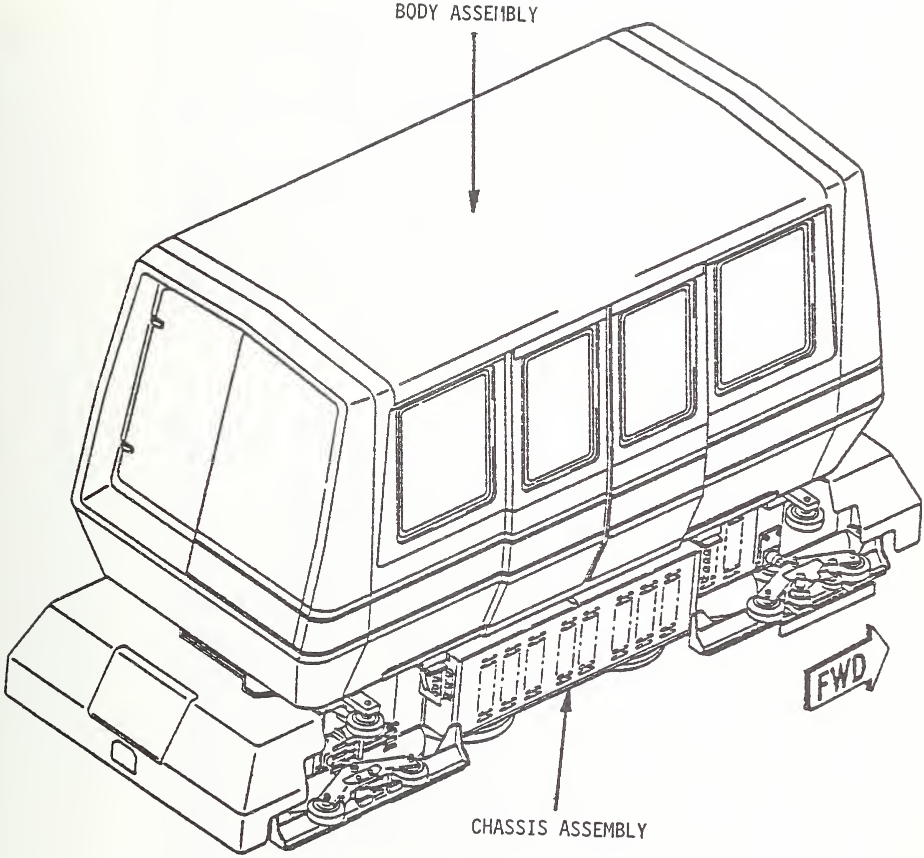
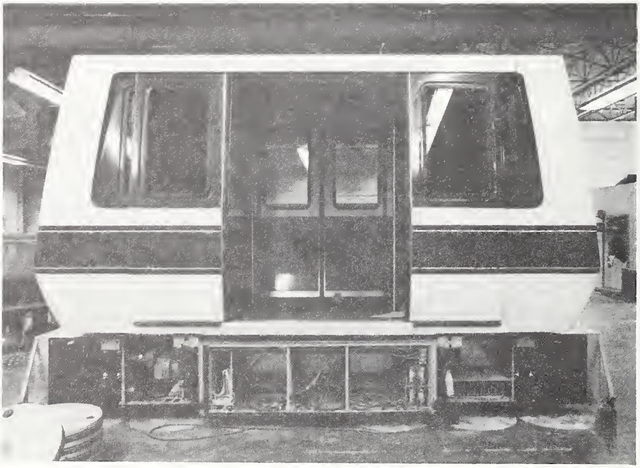


FIGURE 2-6. DUKE VEHICLE SKETCH

OTIS-TTD DUKE PRODUCTION VEHICLE



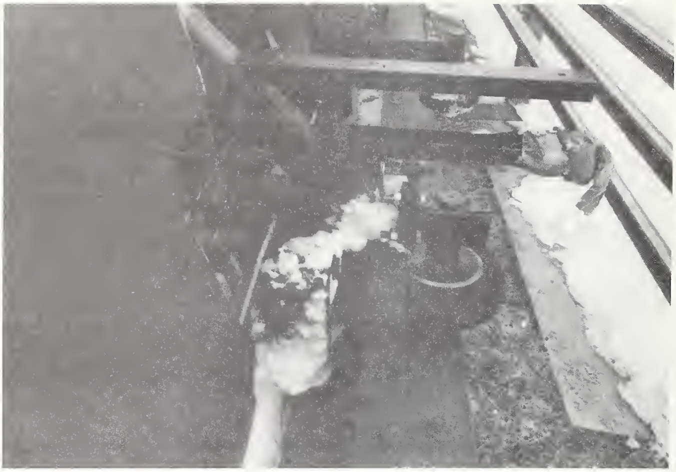
DUKE VEHICLE WITH PROPULSION INVERTER
REMOVED, AND SHOWING INTERIOR

FIGURE 2-7. DUKE VEHICLE PHOTOS

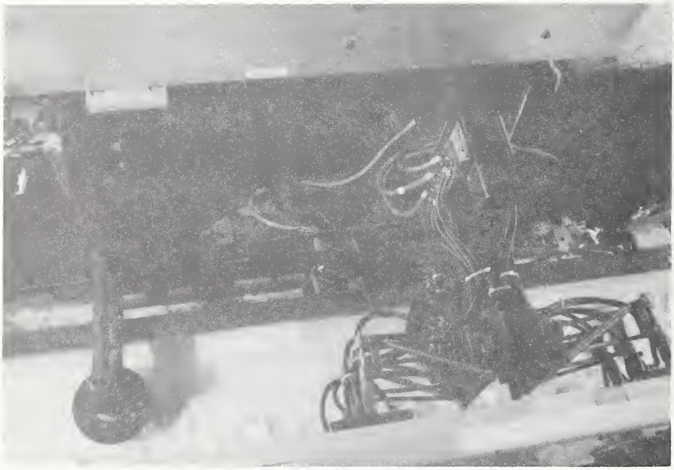
OTIS-TTD TEST VEHICLE REAR VIEW WITH SHROUD

OTIS-TTD TEST VEHICLE REAR VIEW WITHOUT SHROUD

FIGURE 2-8. REAR VIEW OF OTIS TEST VEHICLE

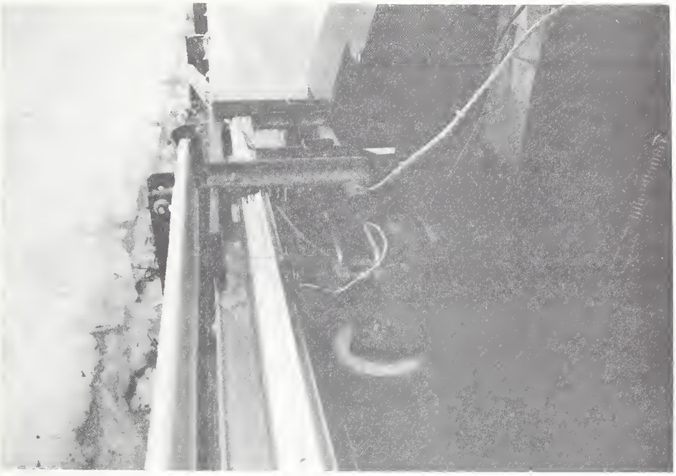


OTIS-TTD TEST VEHICLE REAR TEST TRACK ADAPTOR

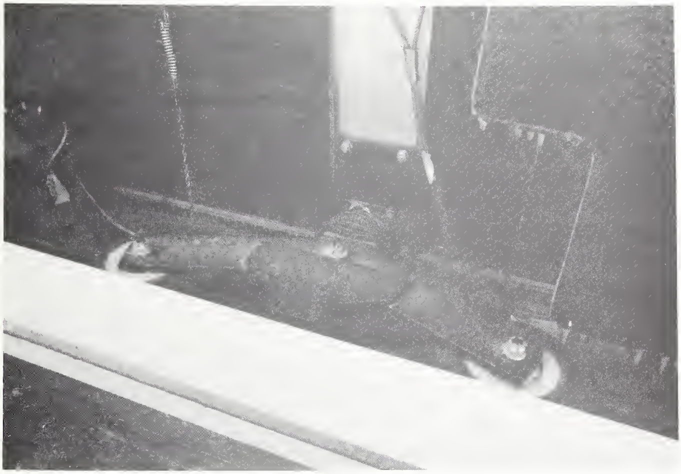


OTIS-TTD VEHICLE FRONT TEST TRACK ADAPTOR
AND POWER COLLECTOR ASSEMBLY

FIGURE 2-9. OTIS TEST VEHICLE ADAPTORS



OTIS-TTD TEST VEHICLE REPRESENTATIVE DUKE HARDWARE



OTIS-TTD TEST VEHICLE LATERAL GUIDANCE BOGIE

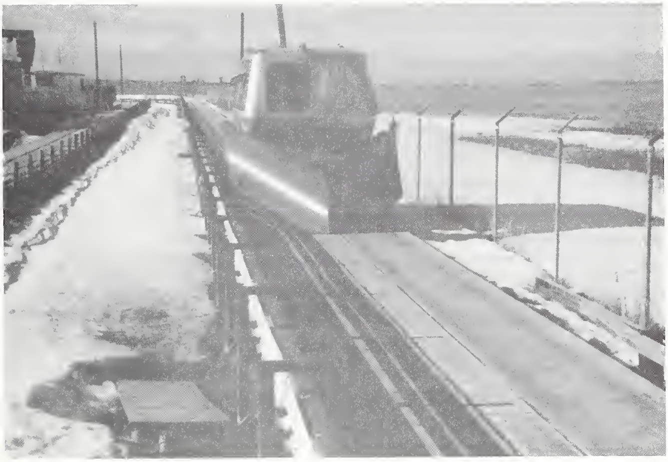
FIGURE 2-10. OTIS TEST VEHICLE HARDWARE

the ride quality and lateral control exhibited by the vehicles used in the winterization test program are not representative of of either those occurring at Duke University or those proposed for DPM installations. The subjective evaluations of the comparative ride quality and ride-quality disturbances were effectively made during the application of precipitation during severe winter weather conditions. The mechanical properties of the representative Duke and DPM vehicle/guideway interfaces were thoroughly investigated through demonstrations, observations, and the recording of test parameters to determine the total effects of the winter conditions upon all critical components during the operation of the OTIS-TTD Duke vehicle at the Denver test track. During the test program, the vehicles were equipped with debris guards, which interface the leading edge of the vehicle's chassis and the guideway flying surfaces, and protective shrouds which cover the ends of the vehicle chassis. This equipment is in the normal vehicle configuration. Also, various protective shrouds, boots, and covers were tried to reduce the effects of winter precipitation accumulations. Additionally, a specialized maintenance snowplow was developed for vehicle installation for removing snow accumulations from the guideway. Figures 2-11 and 2-12 show the Otis test vehicle with winterization modification installed.

2.3 SNOWMAKING EQUIPMENT

OTIS-TTD obtained snowmaking equipment from Ratnik Industries, Inc., because of their extensive experience in the design and installation of snowmaking systems for ski areas and agricultural irrigation. The equipment included snow guns, nozzles, stands, and auxiliary equipment such as hoses, valves, and manifolds for snowmaking operations used to supplement the precipitation levels at the Denver test track.

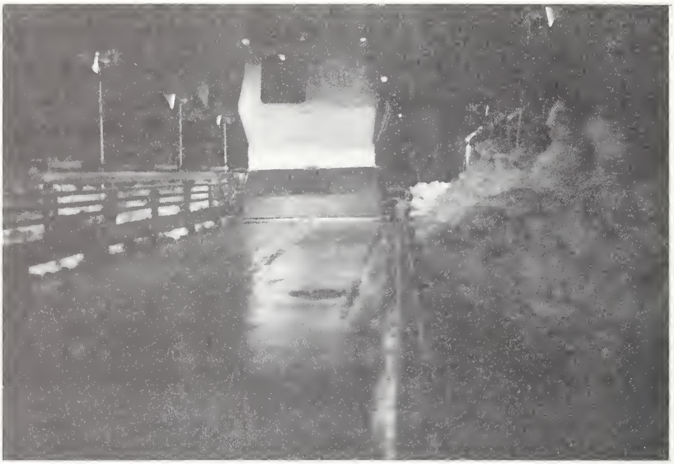
The snowmaking equipment that was installed and used during the first winter season (1978-79) of the winterization test demonstration program included three small snow guns with water and air manifolds that were approximately 200-feet long, which allowed placement of these guns at various locations. Water-pumping cap-



TEST VEHICLE WITH SNOWPLOW INSTALLED AND UNDERWAY

TEST VEHICLE WITH SNOWPLOW INSTALLED 3/4 VIEW

FIGURE 2-11. OTIS TEST VEHICLE WITH SNOWPLOW



OTIS-TTD TEST VEHICLE MAKING AN "ICE" RUN AT NIGHT

FULLY WINTERIZED TEST VEHICLE UNDERWAY IN ICE CONDITIONS

FIGURE 2-12. OTIS TEST VEHICLE SHROUDS AND DEBRIS GUARDS abilities of up to 6000 gallons per hour were provided, along with a compressed-air supply of up to 750 cubic feet per minute. The program received an extremely late start during this season and weather conditions, for the most part, during the months of February and early March were not suitable for snowmaking operations. Some of the difficulties in producing the desired consistency of snow and accurately placing it on the guideway areas were due to insufficient air capacity for the snow guns and disturbances caused by prevailing winds. It was determined via experimentation (trial and error method) that winds over 3 mph and across the axis of the guideway would significantly influence placement of snow accumulations on the guideway surfaces.

During the 1979-80 winter season, a major consideration was the improvement of man-made snowmaking capabilities. The improvements were primarily concentrated in three areas. 1) Additional air supply was provided for the snowmaking equipment. This was doubled from the 1978-79 capacity to 1500 cubic feet per minute. 2) Additionally, the winds were a significant factor in placing the snow were needed and providing a consistent snow coverage. A wind screen was provided at the test site which was approximately 100 feet long and 25 feet high. This allowed snowmaking operations to continue during those times when the prevailing winds reached speeds of up to approximately 15 mph. 3) Modifications were made to the snow gun mounts via a design by Otis Elevator Company which allowed the location and direction of the snow guns to be changed while in operation without having to shut them down or otherwise tamper with the water and air mixtures. This allowed greater flexibility in the placement of snow and a much more consistent man-made snow accumulation. These improvements in the snowmaking equipment in the second season, 1979-80, provided a dramatic increase in the number of man-made snow test days and in the quality of the tests performed and the amount of viable data derived from these tests. Overall the snowmaking equipment in the 1979-80 winter season had the capability of producing snowfalls covering 100 to 200 feet of guideway at accumulation rates in excess of 2 inches per hour. Snowmaking operations were performed with ambient temperature ranges of up to 25°F, and in some cases acceptable wet snows with a moisture content in excess of 30 percent were produced at temperatures up to 30°F.

Man-made snow during the 1979-80 winter season was principally produced using two snow guns, each equipped with a 1-inch nozzle, and allowing each gun to disperse a snow pattern approximately 75 to 100 feet in length-longitudinal to the guideway axis. These two guns were incorporated into the Otis-designed snowmaking mounts for increased flexibility of snow placement. This combination of snowmaking equipment as used in the second season (1979-80), dramatically increased the ability to produce supplemental snows (including 18 test days in the course of the program when supplemental snows were satisfactorily produced). This in turn provided a significant increase in the amount of data that was acquired, and the number of demonstrations run in the test program. Figures 2-13 and 2-14 show snowmaking equipment and operations.

2.4 METEOROLOGICAL INSTRUMENTATION

Temperature, relative humidity, barometric pressure, wind speed, wind direction, precipitation type and rate, snow density and accumulations, and other pertinent weather-forecasting information were all collected at the OTIS-TTD Denver test track throughout the course of the project. All of the climatological observations were made in accordance with the guidelines prescribed in the Federal Meteorological Handbook Number I. A snow measurement kit was utilized in accordance with the U.S. Army Cold Regions Research and Engineering Laboratory of the Corps of Engineers.

Of primary interest during the conduct of the test program were the ambient temperatures present at the test site. The temperatures were continuously recorded on the weather-measure metrograph, which is a recording instrument that simultaneously

WINTERIZATION SNOWMAKING EQUIPMENT INCLUDING WATER PUMP, AIR COMPRESSOR, WATER TANK, FUEL TANK AND AFTER-COOLER

WIND SCREEN IN RAISED POSITION

FIGURE 2-13. SNOWMAKING EQUIPMENT

SNOWMAKING SYSTEM IN OPERATION IN WINTERIZATION TEST AREA

CLOSE-UP OF SNOW GUN IN OPERATION

FIGURE 2-14. SNOWMAKING OPERATIONS

produces analog traces of temperature, relative humidity, and barometric pressure. The temperature sensor on the weather-measure metrograph was initially calibrated, then checked and updated as necessary by the use of two laboratory grade mercury thermometers. The metrograph temperature sensor and the two mercury thermometers were backed up by temperature readings from nickel iron resistance thermometers and reported temperature readings from Buckley Air National Guard Base Weather Station. Relative humidity was continuously recorded on the metrograph, the sensor of which was initially calibrated by the use of a hand-held sling sychrometer and comparison to a relative-humidity indicator that was certified by the manufacturer. The relative-humidity readings were checked and updated on a daily basis as required and any change or alternation to the recorded relative-humidity sensor was verified by the backup instruments and reference to relative-humidity information provided by Buckley Air National Guard Base Weather Station and the National Weather Service, both located in Aurora, Colorado. Barometric pressure was continuously recorded utilizing the pressure sensor in the metrograph on a 24-hour record. This particular instrument was backed up by the use of a continuously-recording barometric pressure sensor at the OTIS-TTD test site and these two instruments were verified by comparison to barometric-pressure readings, corrected to sea level, provided by Buckley Field Weather Station and the National Weather Service. Wind speed and direction were continuously recorded using the Bendix Aerovane.

Additional meteorological information was obtained during tests from the Buckley Air National Guard Base Weather Station and the National Weather Service Forecasting Station. The close proximity of the Buckley Field Weather Station to the test site provided a good backup for weather information. In addition, both of these sources were extensively utilized for test-scheduling purposes in order to optimize the use of the test-program resources by providing the required pre-test conditions and the maximum amount of recoverable information from both test and demonstration. The specific characteristics of snowfalls -- texture, amount of drifting, local variation in accumulation, whether the snow was melting on a warm surface and refreezing or falling cold and retaining its crystalline shape -- and their effect on the system were observed and evaluated subjectively.

3. TEST ENVIRONMENT

A major task of the project was to simulate the conditions considered representative of the worst case or most severe winter conditions to be encountered by a deployed DPM system in a northern U.S. locale. Therefore, every effort was made to duplicate these conditions as closely as possible. It became clear early in the program that all of the critical test-environment requirements could be duplicated at the OTIS-TTD test site, with the exception of snow accumulation with prevailing high winds. This particular condition (high winds) did not allow for accurate measurement of results, or the placement of precipitations. In particular, supplemental precipitations produced by the snow-making equipment were blown out of the test area.

3.1 DESIRED CLIMATOLOGICAL EXTREMES

The twin cities of Minneapolis-St. Paul, Minnesota, have severe winter weather conditions which would produce the required worst-case conditions for operation of a DPM system. The severe weather conditions were established for the test program. The temperature characteristics of Minneapolis-St. Paul during the winter months include a 50-year low temperature of $-34^{\circ}F$ and an average of 158 days per year with a minimum temperature below $32^{\circ}F$. The mean daily temperature is below $32^{\circ}F$ for the months of November through March. Winds in this area during the winter months have peak gusts of 40 to 60 miles per hour and average speeds ranging from 10.4 to 11.4 mph. The 50-year-worst-case peak wind gust is 82 mph.

The winter season in St. Paul is characterized by its length, extremely low temperatures, numerous snow events and high accumulations. The average seasonal snowfall is 46 inches, with the highest single recorded snow event being 16 inches. The seasonal average of snowfalls is 14 per year, more than 9 of which are snowfalls in the range of 1 to 2.5 inches. The predominant amount of snow that falls in this region has a moisture content of less than 10 percent (approximately 12 of the average 14 snow events in a given average year). The other two snow events fall into the moderately-heavy category, which is snow with water content of 10 to 20 percent, and the heavy-wet category which is snow with water content 20 percent or more. The average snowfall accumulation per month ranges from 5.8 inches in November, which is the lightest amount, to 10.7 inches in March, which is the heaviest amount, with only traces being recorded in October.

In order to satisfy the winter weather characteristics as described for St. Paul, the following test conditions were prescribed:

1. Determine the system performance characteristics in tests conducted at the lowest temperature ranges possible (at or below -16^{o}F).
2. Demonstrations necessary to determine the most effective means of snow removal of a single accumulation of up to 16 inches.
3. Snow accumulation at rates of up to 2 inches per hour with the water content ranging less than 10 percent through 30 percent or more (slush).
4. The man-made production of freezing rain or sleet to a total accumulation of 1 to 2 inches.

3.2 CLIMATOLOGY OF TEST LOCATION

3.2.1 Historical Weather Data

The OTIS-TTD test site experiences winter climates which can duplicate the severe winter weather conditions representative of Minneapolis-St. Paul. The typical low temperatures experienced in any one year range down to approximately -15^{o} to -20^{o}F. The cold weather winter season lasts from approximately the last part of November through the first part of March. This winter season may be broken by periods of warming weather above freezing for the average daily temperatures. It is quite characteristic of the Denver-area climate to have daytime peak ambient temperatures during the winter seasonal months that are well above freezing. This produces significant melting of snow accumulations. Typical snow events range from 2 to 5 inches of snowfall with a moisture content of approximately 10 percent. These snowfalls quite frequently melt in approximately 2 to 3 days. Snowfalls of heavier amounts occur during the winter season with amounts of up to 18 inches considered likely, particularly in the late fall or early spring. These snowfalls sometimes occur with air temperatures in excess of freezing and melt very quickly even though they have a heavier moisture content. At the OTIS-TTD test site, the snowfalls are typically accompanied by high-level ground winds averaging 30 mph and at times with gusts in excess of 60 mph. Due to the open and unprotected location of the test site, drifting is likely to be severe making the site inaccessible. Because of the high winds frequently associated with the severe snowstorms, the supplemental man-made precipitation in the form of snows was considered the most accurate and reliable method of placing the appropriate types and heavy accumulations consistently over the guideway system.

Historical weather data that is representative of the OTIS-TTD test site has been collected at the National Weather Service Station in Denver. This information, as has been documented over the past 20 to 30 years, is presented in Appendix B.

3.2.2 Climatological Conditions, 1978-1979

The winterization test and demonstration program contract was let November 21, 1978. Because of the long lead time associated with the rental and purchase of snowmaking equipment and test instrumentation, effective operation of the test and demonstration program did not start until late January 1979. The weather conditions during the winter season of 1978-1979 included several days of extremely cold temperatures occurring in early December and just prior to the Christmas holidays. These cold temperatures persisted for 3 to 4 days at a time and yielded low temperatures in the range of -16° to -17°F. The temperatures in the latter portion of January and February were above normal for that period of time. The snowfalls that occurred during 1978-79 were below normal both in number and quantity of snows deposited. During the winter season three individual 3- to 5-inch snowfalls with a water content of 5 to 20 percent fell at various times. A 3- to 4-inch snowfall of heavy wet snow with a water content in excess of 30 percent fell on March 8, 1979, and turned to slush on a warm guideway surface. Prior to the beginning of the program, a 6-inch snowfall with a water content of 16 percent, fell during high wides which resulted in drifts of up to 24 inches in depth. The most significant snow event, again with high winds, was an unpredicted 8- to 10-inch snowfall with a water content of 25 percent and with drifts of over 24 inches in depth. The average accumulation throughout the entire guideway region was 20 inches.

3.2.3 Climatological Conditions, 1979-1980

The winter of 1979-1980 was characterized by average temperatures with periods of above-normal temperatures and no periods of significantly below-normal temperatures. Snow events were about average in number with above-average accumulations. Temperatures in November were too high for the production of snow (over 25°F) except for 1 week. At that time a significant snow event occurred, accompanied by winds in excess of 60 mph. The storm resulted in snow accumulations of 15 inches with dirfts of up to 2 to 3 feet on the guideway. Snow events for the month of December totaled six: two with insignificant accumulations (less than 1 inch); and four with accumulations ranging from 3 to 10 inches and with moisture contents of 15 to 20 percent. Temperatures during the first week of January were too high for snowmaking operations, but temperatures over the following 2 weeks permitted the production of man-made snow on an intermittent basis. Temperatures during the last week were suitable only for icing tests (25°F to 30°F). Snow events for January totaled 3: one significant event, supplemented by snowmaking operations;

and two events with accumulations of less than 2 inches. For the month of February snow events totaled three: one significant event with an accumulation of 5 to 6 inches, drifting to depths of up to 12 inches, and with a moisture content of 15 percent; and two events with accumulations of less than 2 inches. Significant climatological conditions during March included one snow event with an accumulation of 2 to 4 inches, which drifted to somewhat higher accumulations on the guideway, and several days with overnight low temperatures ranging from -2^{o}F to 16^{o}F.

3.3 SUPPLEMENTAL WEATHER MEASURES

OTIS-TTD proposed two basic supplemental weather measures: 1) the transportation of the test vehicle to Frazier, Colorado, to undergo cold soak testing to determine the influences of extremely low temperatures on vehicle subsystems, and 2) the addition of snowmaking equipment to provide supplemental precipitations during cold weather operations. The transportation of the test vehicle to Frazier, Colorado, as part of the test program, was not necessary due to the advent of an extremely cold day with attendant overnight low temperatures early in December 1978. The Otis Duke vehicle was exposed to a cold soak for 10 hours at temperatures starting at 0^{o}F and gradually decreasing to -13^{o}F. The lowest temperature during the test was approximately -17^{o}F. The snowmaking equipment as previously described was installed at the OTIS-TTD Denver test site for the addition of precipitations to be utilized to simulate key elements of the severe winter weather conditions during system and subsystem operations. The snowmaking was used during both winter seasons but much more extensively in 1980. The system, as installed, allowed the placement of snows with a water content of from 20 percent to well in excess of 30 percent on the vehicle, vehicle elements, guideway, and associated wayside equipment installed in the winterization test area. Precipitation rates of 2 inches per hour were produced on a regular basis. It was found that the use of the snowmaking equipment allowed much more control over the precipitation that fell for test purposes, and also allowed a much higher degree of flexibility in which type of tests would be performed. Therefore, the amount of viable test data and demonstrations that were produced during 1980 was obtained predominantly by utilizing the supplemental precipitation measures as installed at the test site.

Additional supplemental precipitation in the form of freezing rains and sleet was produced utilizing spray nozzles to produce a fine rain-like effect on the guideway, associated hardware, and vehicle. Additional ice accumulations representative of melted-and-refrozen precipitation were produced by flooding the guideway and associated hardware with water and allowing it to freeze at the lower tmeperatures, producing glaze-ice conditions. These supplemental icing measures were necessary due to the fact that the Denver-area climatology does not normally include those conditions that produce freezing rains or sleet. Although not expected or anticipated in the Denver climate, two nights of heavy frosting occurred during the 1980 portion of the test program. This allowed an evaluation of the effects of frost on the vehicle system and operation.

4. DEVELOPMENT OF DETAILED TEST PLANS

A test plan was developed prior to the beginning of testing and demonstration to provide a unified overview of the complete DPM winterization test and demonstration program. It provided the baselines for organizing, structuring, and guiding test implementation and for the preparation of comprehensive test procedures. The proper execution of this plan yielded the information required to properly assess the OTIS-TTD DPM system capabilities to operate reliably during severe winter weather conditions. This plan development was based on the identification of critical subsystems in view of the impact of severe winter weather conditions. The test plan includes detailed descriptions of the testing to be performed, the methods of data acquisition and handling, the required resources to perform the test and demonstration, schedules, description of subsystems and facility modifications, and a basic outline of the test procedures.

4.1 IDENTIFICATION OF CRITICAL SUBSYSTEMS

A comprehensive review of the history and experience of the OTIS-TTD system and related hardware with regard to the demands imposed by severe weather operating conditions, yielded a listing of critical subsystems and hardware which would be most sensitive to the severe winter weather conditions proposed in the test and demonstration program. The Otis system for DPM winterization demonstration is based on the vehicle and equipment configurations installed at the Duke University Medical Center in Durham, North Carolina, along with use of the existing OTIS-TTD test-track guideway in Denver, Colorado. The basic HOVAIR air suspension and LIM propulsion systems provide the functions of support, propulsion and service braking and do not depend on traction. This means that Otis vehicles can operate normally on guideways which are wet and slippery and even ice-covered. The vehicle is controlled longitudinally via use of an on-board microprocessor-based control subsystem which provides intelligent determinations with regard to vehicle speed, acceleration and jerk control. The vehicle switching as proposed in the DPM installations utilizes a passive guideway switch rail and incorporates an on-board vehicle switching mechanism. Vehicle location and safety are assured via monitoring in a fixed block system utilizing a segmented signal rail. Additionally, vehicle monitoring is performed utilizing a continuous wayside/vehicle communication link.

The basic approach utilized in the operation of the OTIS-TTD DPM system with the impacts of the severe winter weather conditions was to provide continuous vehicle operation during precipitations in cold weather to allow the precipitation accumulations to be continuously removed from the guideway and associated hardware without causing system shutdowns or outages. This particular approach was utilized with ample consideration for not allowing degradation of system availabilities while maintaining adequate levels of service during winter precipitation events.

4.1.1 Vehicle-Related Critical Subsystems

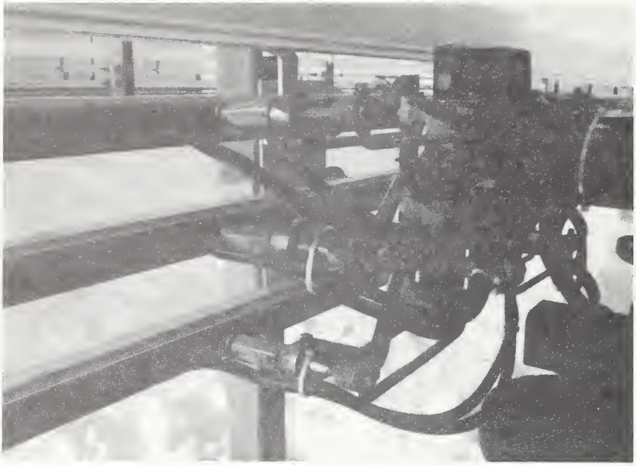
4.1.1.1 Vehicle Lateral Guidance - Lateral guidance is provided by a dual-wheel articulated bogie providing suspension through a sliding bearing and damped torsional spring (Figure 4-1).

4.1.1.2 Retention and Switching Arm Assembly - The vehicle guideway retention and route switching are performed dually utilizing this particular mechanism with on-board controlled switching by moving or extending an arm to one side or another (Figure 4-2).

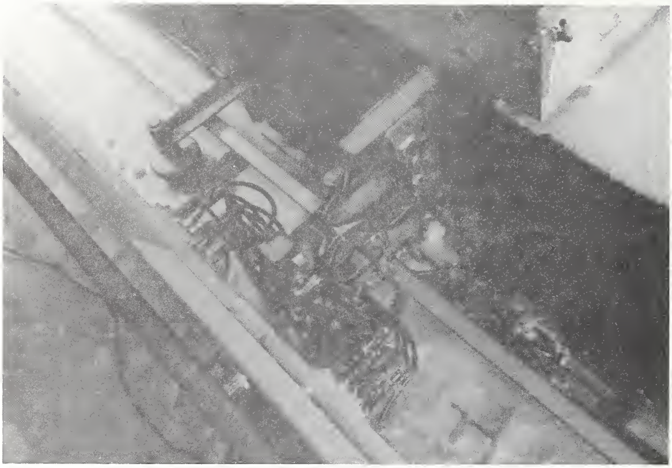
4.1.1.3 Vehicle Power Collection Subsystem - Power is collected from the guideway power rail distribution system via two axis-articulated power collection brushes containing two sets of contacts for each power rail (Figure 4-3).

FIGURE 4-1. OTIS LATERAL GUIDANCE AFTER CONTINUOUS SNOWSTORM OPERATIONS

FIGURE 4-2. RETENTION AND SWITCHING INSTALLATION



OTIS TEST VEHICLE POWER COLLECTORS IN RAILS



OTIS TEST VEHICLE POWER COLLECTOR
ASSEMBLY ON GUIDEWAY IN SNOW

FIGURE 4-3. VEHICLE POWER COLLECTION

4.1.1.4 Vehicle Communication Antenna - The vehicle receive/ transmit communication antenna loop is mounted on the lateral guidance bogie to provide interface with the continuous communication antenna mounted on the guideway (Figure 4-4).

4.1.1.5 Primary Air Suspension Air Pads - The primary vehicle vertical suspension is produced via an air cushion lift provided by air pad assemblies (12 in number) that are installed on the underside of the OTIS-TTD vehicle chassis (Figure 4-5).

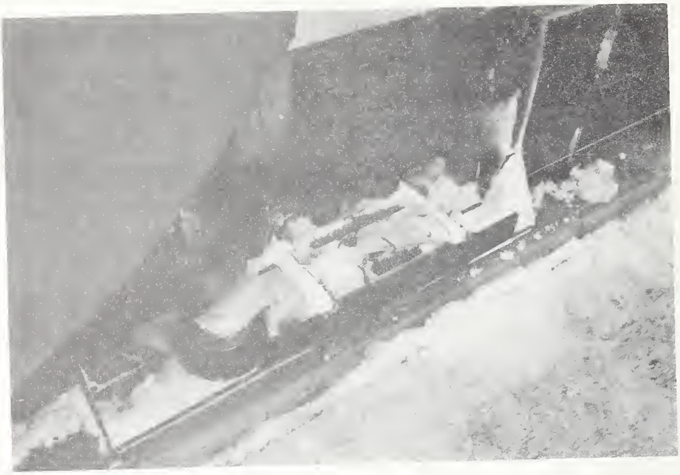
4.1.1.6 Primary Suspension Blower Motors and Manifolding - These components produce the compressed air utilized in the air pad assemblies and distribute it throughout the vehicle (Figure 4-6).

4.1.1.7 Secondary Suspension - The vehicle contains a secondary vertical suspension system decoupling the vibratory motion experienced by the chassis from the vehicle body (Figure 4-7).

4.1.1.8 Vehicle Chassis Shrouds - Shrouds are normally provided on the OTIS-TTD vehicles, covering the ends of the vehicle chassis and providing emergency-egress steps, protection for the chassis, guideway debris removal, as well as integral bumpers and aesthetic properties (Figure 4-8).

4.1.1.9 Vehicle-Mounted Tachometers - These tachometers are interfaced with the guideway suspension rail and produce the velocity feedback information that is provided for the on-board control systems (Figure 4-9).

4.1.1.10 Vehicle Signal Rail Collectors - These are provided by utilizing the same hardware and techniques as in vehicle power collection (Figure 4-10).

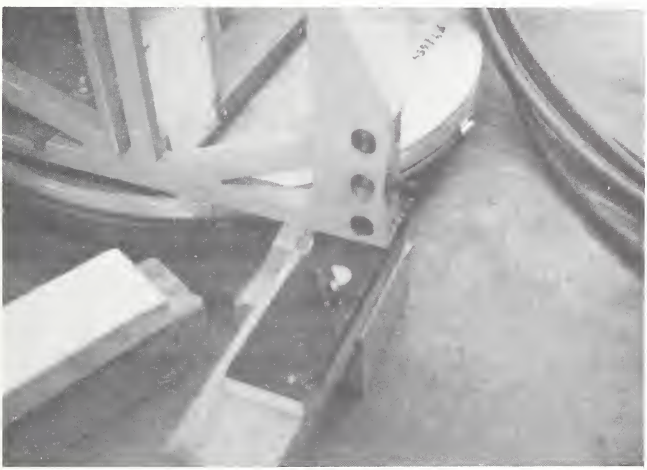


OTIS TEST VEHICLE ANTENNA
INSTALLATION AFTER SNOWPLOW OPERATIONS

GUIDEWAY ANTENNA TEST SECTION DURING HEATER TEST ON RAILS

FIGURE 4-4. VEHICLE COMMUNICATION ANTENNA

DUKE VEHICLE AIR SUSPENSION PADS DURING INSTALLATION



AIR SUSPENSION PAD INSTALLED UNDER VEHICLE CHASSIS

FIGURE 4-5. VEHICLE AIR PADS

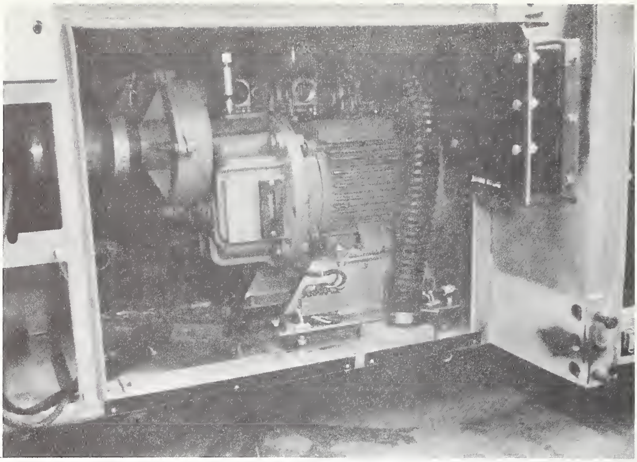


FIGURE 4-6. VEHICLE AIR SUSPENSION BLOWER

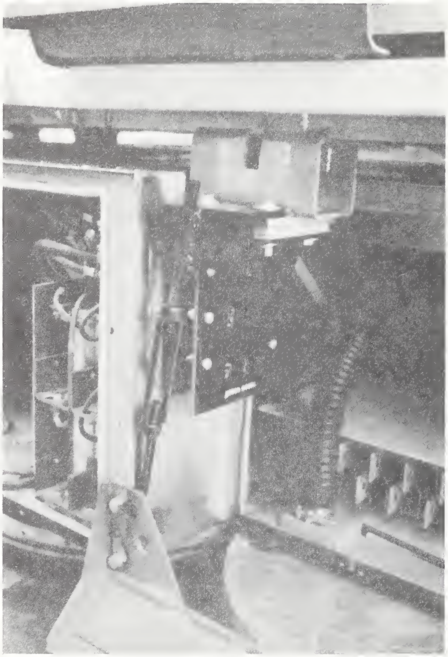
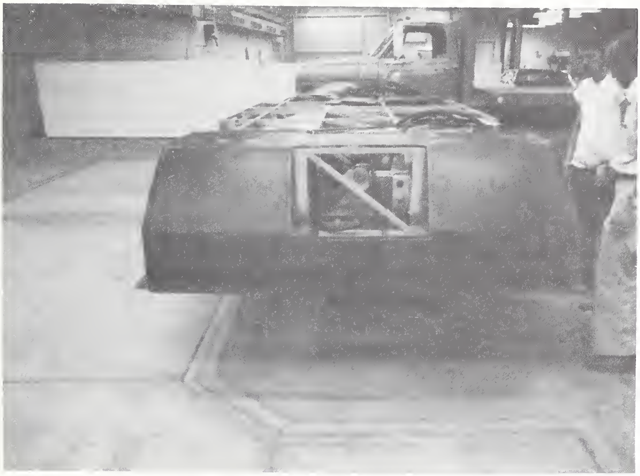


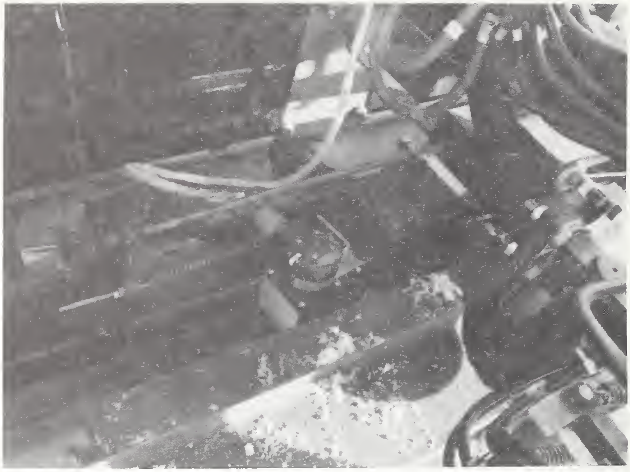
FIGURE 4-7. SECONDARY SUSPENSION SHEAR MOUNT



DUKE VEHICLE SHROUD DURING VEHICLE ASSEMBLY

CLOSE-UP OF OTIS TEST VEHICLE SHROUD AND DEBRIS GUARD INSTALLATION UNDERWAY IN ICE

FIGURE 4-8. VEHICLE SHROUDS AND DEBRIS GUARD

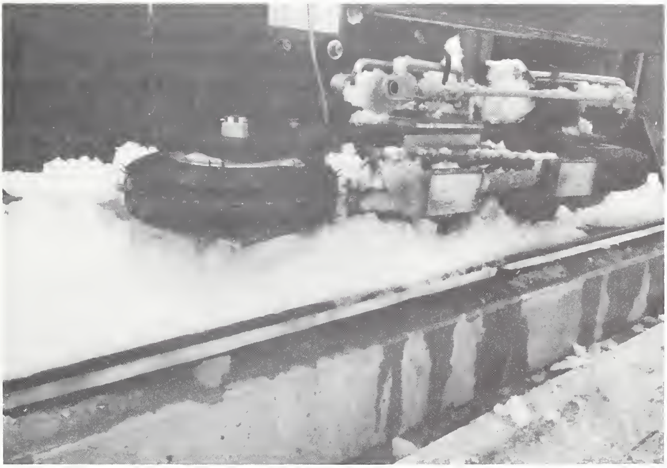


OTIS TEST VEHICLE TACHOMETER INSTALLATION

SAME INSTALLATION AFTER SNOWPLOW OPERATIONS

FIGURE 4-9. VEHICLE TACHOMETER

DUKE POWER COLLECTOR ASSEMBLY WITH
SIGNAL COLLECTOR ON BOTTOM OF STACK



OTIS TEST VEHICLE SIGNAL COLLECTOR INSTALLATION AFTER
CONTINUOUS SNOWSTORM OPERATIONS WITH SIGNAL BRUSHES REMOVED

FIGURE 4-10. VEHICLE SIGNAL COLLECTORS

4.1.2 Guideway-Related Critical Subsystems

4.1.2.1 Power Rails - The power rails utilized by the OTIS-TTD DPM system are Howell stainless steel face aluminum rails supported at 7.5-foot intervals at the OTIS-TTD test track (Figure 4-11).

4.1.2.2 Guidance Rails - The guidance rail installation in the winterization test area at the OTIS-TTD test track consists of box beam aluminum guidance rails that perform vehicle guidance as well as vehicle grounding and support the wayside continuous antenna line, which is the guideway portion of the wayside/vehicle communication system and is interfaced to the vehicle through a helix wire communication antenna loop mounted on the guidance bogie assembly (Figure 4-12).

4.1.2.3 Concrete Flying Surface - In the OTIS-TTD DPM system, the guideway flying surfaces are located on either side of the center reaction rail in the guideway and are smooth-troweled and sealed concrete surfaces providing a smooth interface for the HOVAIR air suspension system air pads on board the vehicle.

4.1.2.4 Emergency Braking Surfaces - Emergency braking surfaces approximately 6 inches wide are provided at the outboard edges of the concrete flying surfaces and are suitably textured to provide adequate emergency braking deceleration levels when contacted by the vehicle on-board brake pad assemblies (Figure 4-13).

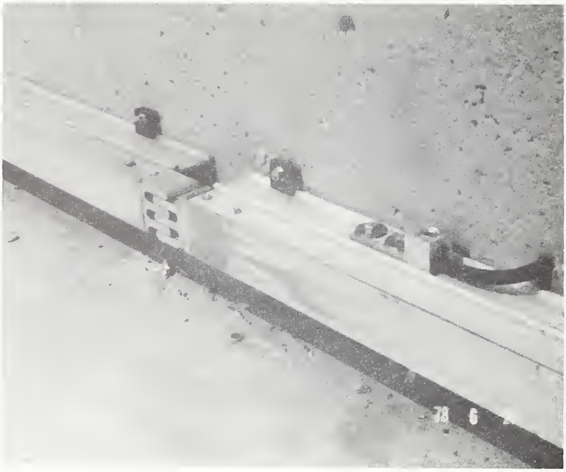
4.2 DEVELOPMENT OF POTENTIAL SOLUTIONS

The potential solutions deemed necessary by previous operating history and by experience were developed in testing programs operated by Otis Elevator in the past. A number of pre-test modifications and design iterations in hardware on the OTIS-TTD vehicle and guideway would meet the demands posed by the severe weather conditions to be implemented in the winterization test

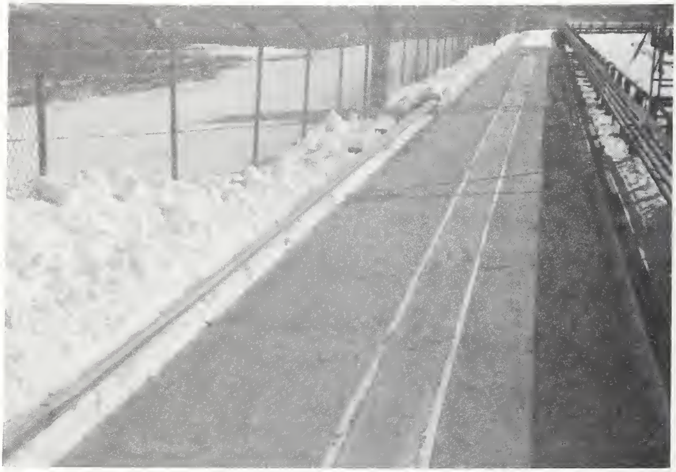
OTIS TEST TRACK POWER INSTALLATION

POWER RAIL CLOSE-UP
SHOWING TEMPERATURE
SENSOR DURING HEATING
TEST

FIGURE 4-11. GUIDEWAY POWER RAILS



DUKE UNIVERSITY SYSTEM GUIDANCE RAIL INSTALLATION



DUKE GUIDANCE RAIL AS INSTALLED
AT THE TEST TRACK IN SNOW BANK

FIGURE 4-12. GUIDEWAY GUIDANCE RAILS

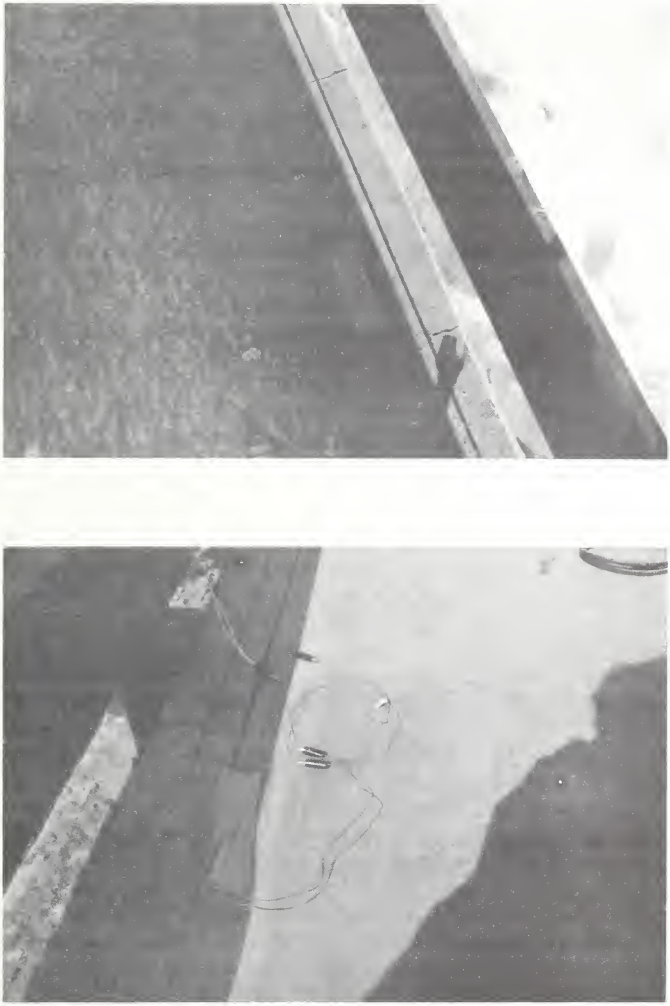


FIGURE 4-13. GUIDEWAY EMERGENCY BRAKE SURFACES WITH HEATER-WIRE SLOTS AND TEMPERATURE SENSORS

and demonstration project. One of the primary objectives in the winterization program was to see if vehicle operation in an automated mode would be possible for a wide range of adverse weather conditions. Vehicle and guideway subsystem reliabilities in severe weather conditions would have to be such to preclude unnecessary nuisance shutdowns of vehicles. At the same time, the cost baselines had to be met. The least cost exposure approach was always used initially when it could be determined that it would offer an acceptable level of operational reliability and availability.

Vehicle lateral guidance assemblies were winterized to the extent that flexible boots were installed over the sliding arm to keep this particular member clear and free of ice and snow as it is required to operate into the sliding bearing assembly. The rotation of the lateral guidance tires provided no significant potential for loss of system availability due to the impact of severe winter weather conditions, since these assemblies interface the guidance rail, which will be discussed later in this section.

The retention and switching are performed on board the vehicle. The winter problem area implications of this particular subsystem are that ice and snow buildups or cold temperatures might slow down or otherwise impede a switching maneuver. The Duke hardware that was installed on the test vehicle utilized in the 1978-79 season has a slow mechanical switch mechanism. The actuation of the mechanism is not applicable to DPM hardware, but the mechanism itself is representative of that which would be installed by OTIS-TTD as part of a DPM vehicle. The retention and switching arm assembly was protected for winterized operations by two different steps: 1) the movable arm was covered with a flexible boot to prevent the buildup of ice and snow in the horizontal surfaces of the sliding arm, preventing or slowing motion from one side to the other, and 2) the vehicle body/chassis interface was shrouded and closed out to provide sheltered space for the actuation monitoring and locking of this switching arm. This shroud completely enclosed this area, preventing precipitation from entering and affecting any of the above-mentioned components.

Power collection on board the vehicle initially was operated in the winterized mode utilizing the basic system hardware with only the addition of a dry silicone-base low-temperature lubricant in some of the moving-joint areas. It was anticipated that if problems did occur in the power collection area during the operation of the test and demonstration program, heating of localized areas or the installation of protective covers would be utilized to improve these particular operations.

The vehicle-mounted communication antenna, already being a potted and sealed unit, was not in itself modified for winter operations. Its relative location on the vehicle was changed to allow some improvement in the tolerance of the amount of snow and ice buildup in the areas underneath the guidance rail, and to allow better dispersal of the snow in this region from the guideway LIM reaction rail and concrete flying surface. The antenna was left in approximately the same location on the vehicle but was raised 10 to 12 inches to a guideway interface point above the vehicle guidance rail.

The vehicle air pad assemblies, as a part of the vertical suspension system on board the vehicle, have a built-in natural winterization potential. They are naturally able to clear the guideway flying surface of some amount of snows and water, utilizing the effect of the air and the flexible membrane in close contact with the guideway flying surface. The air that is produced for levitation by the vehicle vertical suspension blower assemblies is heated in its compression.

The OTIS-TTD DPM vehicle is configured with dual suspension blower/assemblies using common manifolds to supply the air necessary to suspend the vehicle above the guideway flying surface. The two suspension blower assemblies are redundant (with one on inactive standby) for reliability purposes. One of the potential implications of excessive winter precipitation accumulation on the guideway flying surfaces, such as ice and snow, is that the vehicle could use higher floatation air volumes as this surface becomes more irregular. The control configuration of these suspension blowers to sense the vehicle manifold pressure and call on the operation of a second suspension blower, in the event a reduction of manifold pressure occurred, was determined to be a feasible approach and would be incorporated in the test demonstration program if necessary.

The vehicle body secondary suspension assemblies were investigated to determine their susceptibility to variations in spring rates brought about by extremely cold temperatures. Some design effort was performed to identify materials and material combinations for these secondary suspension mounts which would perform more acceptably in low temperature environments.

Vehicle chassis shrouds are normally installed on the OTIS-TTD Duke vehicles along with a debris guard which provides a protective closeout for the leading edge of the chassis and a means by which to remove debris from the guideway ahead of the vehicle. The effects of the severe winter weather conditions prompted, on more than one occasion, the redesign and modification of these vehicle chassis shrouds and associated debris guards. The capability of the debris guards to remove ice and snow accumulations from the guideway flying surface determined to a great degree the capability of the vehicle to operate through various winter precipitation conditions. This information was available and based on previous information from testing conducted by Otis Elevator Company. The chassis shrouds themselves were reinforced and provided with some guideway surface closeouts to facilitate the plowing of snow accumulations in front of the vehicle. Additional modification of the chassis shrouds is possible to build into their contour the design of an actual cow-catcher or snow prow detail to additionally facilitate the removal of ice and snow accumulations. The incorporation of the cow-catcher or snow prow was not performed initially in the program and would not be unless it was determined later to be a requirement for successful system operations.

The vehicle tachometers which provide the feedback to the vehicle on-board longitudinal control systems interface the guideway suspension rail, and that suspension rail will be additionally discussed later. Heating of this rail is necessary to keep it free of ice and snow accumulations for this and other implications. The tachometers themselves are environmentally sealed and were additionally provided with covers to protect them from direct impact with ice or hard snow obstructions and, further, to prevent the buildup of frozen accumulations from various other sources from affecting the mechanical operation of the tachometer.

Signal collection on board the OTIS-TTD test vehicle was accomplished utilizing the same hardware and equipment as in power collection. The same initial philosophy as was used with power collections was maintained: that just dry low-temperature lubricants should be used in those pivot areas where deemed necessary and that heating or covers in critical areas should be provided as necessitated by results of tests and demonstrations later in the program.

Solutions to the problems imposed by icing and snow accumulation on guideway power rails were proposed earlier in the program for evaluation during the demonstrations. The primary application to solve the winterization impacts on this subsystem was resistance wire heating that was supplied on the wayside and routed in the power rails, keeping them warm to prevent the formation of ice and frost. In the test site installation at the OTIS-TTD test facility in Denver, this resistance heating was supplied by a separate infinitely-variable circuit to allow the evaluation of various heating power levels. The industry experience, at this particular point in time, has been a magnitude of approximately 15 watts/ft for power rail heating. Otis initially powered these rails at 11 to 11.5 watts/ft, which resulted in successful system operation, as predicted. However, a comparison of stabilized temperatures versus weather conditions (i.e., temperatures and winds) indicated that changes in power levels could be made during the test program to optimize the power consumption to provide reliable operations and yet allow conservation of the energy resources that would be consumed in a DPM deployment. Additionally, power rail covers, sometimes described as insulator covers, were also used and their effects were noted. Various other types of covers were either evaluated, demonstrated, or analyzed for their application to the DPM system and their ability to solve the winter precipitation freeze problem on the power rails.

The guidance rails used at Duke University were installed at the Denver test site in a 180-foot length of the winterization test area. These aluminum rails, which are supported 8 to 10 inches above the guideway surface at 7.5-foot intervals, have provisions for installing resistance wire heaters. The heaters in the guidance rail are deemed necessary for the Otis system, which also uses the guidance rail to provide vehicle grounding through a set of ground collectors which run on the surface of this rail. In order to ensure the integrity of this ground contact, the rail surface was resistance wire heated to remove any accumulations of ice or snow.

The guideway wayside continuous communications antenna (basically a helix wire closed inductive loop transmission and receiving system designed by Otis) was installed at the OTIS-TTD test facility in the winterization test area. For test purposes, it was located just above and at the base of the DPM guidance rail. This particular antenna needs to be in close physical coupling with the vehicle-mounted antenna (i.e., 1 to 2 inches). The effects of snow and ice accumulations on this particular antenna have not been evaluated and were unknown at the beginning of the test program. It was felt the winterization effects would be minimal, but some low-level heating could be applied to this particular subsystem if it were deemed necessary.

The guideway flying surface consists of two strips of concrete on either side of the guideway centerline, separated by the LIM reaction rail. They are approximately 24 inches in width with the surface being produced by concrete forming and finishing techniques to a standard highway tolerance of 1/8 of an inch in 10 feet. A concrete sealer is then applied to provide a flat smooth surface for the interface of the air pads in the vehicle vertical air suspension system. The flying surface is not required to be totally free of ice and snow accumulations, but significant buildups of ice and snow which would raise the vehicle off the guideway and reduce the available propulsion thrust by increasing the gap in the LIM must be prevented. The approach used to keep this guideway surface free of ice and snow accumulations was twofold:

1. A normal circulating vehicle was equipped with debris guards which wipe the leading edge interface between the vehicle chassis and the guideway flying surface. These debris guards were supplemented by vehicle chassis shrouds which assisted the plowing and removal of snowfall accumulations from the guideway. When pushing the snow in front of the vehicle, the snow slid to the sides and out through the open guideway walls; in this way the accumulations were dispersed from the guideway surface area.

2. The HOVAIR air suspension system on board the Otis vehicle has a natural capability to remove certain minimal amounts of snow and/or ice. The compressed air and flexible membrane acts as a wiper on the flying surface, pushing small amounts of snow and ice off the flying surface.

In the first winter season (1978 - 1979) the flying surfaces at the OTIS-TTD Denver test site were covered with a hydrophobic coating, a material used to mitigate ice adhesion to the concrete guideway flying surfaces. This material proved to be successful by significantly reducing the ice buildups on the guideway surface. In the second season (1979 - 1980), it was discovered that this particular hydrophobic formulation was very similar in characteristics to a standard guideway sealer that Otis Elevator had previously used and tested. In the second season, this achrychlor concrete sealer was used in lieu of the hydrophobic coating with essentially the same results.

The Otis DPM guideway configuration contains emergency braking surfaces that are 5 to 6 inches in width and located outboard of the concrete flying surfaces. These particular surfaces are textured to produce a uniform roughness by sandblasting the concrete. They are located in the area that allows the vehicle emergency brake pads to come in contact with this surface when air suspension is lost on the vehicle. Otis has done extensive previous testing to verify the integrity of this braking system and the consistency of braking results produced through various temperature extremes and surface characteristics from wet to dry. A solution to the winterization problems imposed upon this particular subsystem was resistance heating wires installed in these braking surfaces. This brake surface heating wire installation was completed after the brake surface was prepared by sandblasting. Slots were cut into the concrete surface to allow the installation of the wires. The wires were held in place and the slots filled by an epoxy system containing silica sand which retained approximately the same surface texture as the sandblast concrete and created a good tight integral bond to the concrete. The heated brake surface areas at the Otis test-track site used for winterization test and demonstration are approximately 150 feet in length. They were supplied with heating power by an independent infinitely-controllable electrical circuit. The initial power level used for heating the brake surface was approximately 30 watts/ft. The variable control of these heater circuits allowed further optimization of the actual power level required to maintain the integrity of the braking coefficients on these surfaces during the test and demonstration program.

4.3 PRIORITIZATION OF TEST ACTIVITIES

Once the winterization test plan was developed, a program priority-based matrix was established to identify those particular test runs or sequences that were of primary importance to the demonstration program. The emphasis of the winterization test and demonstration program was to demonstrate reliable automatic operation of vehicles in system conditions with the influence of severe weather conditions. This correlates well with OTIS-TTD's general winter operational philosophy of maintaining vehicle circulations during inclement weather (i.e., severe winter weather conditions) to prevent the excessive accumulations of snow or ice. The priority of specific tests that were scheduled during the test and demonstration program was influenced to a large degree by the prevailing ambient temperatures at the test site.

The initial approach in prioritizing was to determine the projected temperature ranges for the upcoming test day or test week, then, within that temperature range, to produce a priority of the various test sequences desired. The test-sequence matrix became rather complex because of the number of variables to be introduced as potential weather conditions. Some of these potential variables included temperature, precipitation type, precipitation rate, precipitation density and consistency, and wind speed and direction. Some control was possible due to supplemental man-made snow which allowed selection of the type of snow accumulation rate and water content, within the capability of the snowmaking equipment. The production of man-made snow was also influenced by the air temperature and the direction and intensity of the winds. In 1979, it was possible to produce consistent applications of man-made snow only at extremely low wind speeds. The capability to produce man-made snows with accompanying wind velocities was improved considerably in the second season of the winterization test program.

A two-dimensional test-priority matrix was established early in the program prior to operating any specific test sequences or demonstrations. This matrix established desired test sequences or procedures within available temperature ranges, and provided the following information of note:

1) At temperatures below $0^{\circ}F$, the test sequence with the highest priority was vehicle cold soak, followed by the production of maximum snow accumulation depth on guideway, representative of accumulations during periods of system shutdown.

The next highest priority was the circulation of an automatically operating vehicle in a system environment with snowfalls with a moisture content of less than 15 percent.

2) In the temperature range of 0° to $20^{\circ}F$ (the predominant range of overnight low temperatures at the Denver test site) the highest priority was assigned to the test sequence for automatically circulating a normal operating test vehicle in snowfalls with a moisture content of 15 to 30 percent. The second highest priority was the production of maximum snow depth with a moisture content of less than 15 percent on the guideway, and automatically circulating vehicles in such an environment.

3) In the temperature range of 20° to $30^{\circ}F$, priorities were assigned to various test sequences. This particular temperature range allowed snowmaking operations in the lower half of the range, but presented considerable difficulties for manufacturing snow in the upper half of the temperature range. The highest priority test sequence was to produce a maximum depth accumulation of snow on the guideway for removal. The second highest priority was the test sequence of automatically circulating a vehicle through snowfalls with a moisture content in excess of 30 percent.

4) In the temperature range of 25° to $35^{\circ}F$, the tests were designated specifically as those tests that could be performed with natural snow accumulations. The highest priority was assigned to circulating and automatically operating the vehicle through glaze ice. The second priority was assigned to circulating an automatically operating vehicle through rime-ice accumula-

tions. The difference between the two icing conditions was that the glaze-ice surface was produced with large amounts of water applied to the guideway and vehicle surfaces by the flood method, whereas the rime ice was produced by subjecting cold surfaces to very fine water sprays, which produce irregular surfaces and ice formations. The next highest priority in this particular temperature range was to produce icing conditions on a stopped vehicle, placed in an open area on the guideway.

Whenever acceptable test conditions were the result of natural snow events, particular test times were scheduled according to weather-forecasting information and the time identification when snow events were to take place. The affected test sequences were thus re-arranged in priority to take advantage of the natural snowfalls. Being able to take advantage of natural snow conditions at the OTIS-TTD Denver test site was known to have some drawbacks. Some of these became apparent when, during major storm events, the test site could not be reached via normal highway travel because of the severity of the attendant snowfalls and wind conditions. One particular event such as this occurred in each winter season. The test-priority matrix, as partially described above, is based on test sequences versus temperature ranges and is shown in Figure 4-14.

4.4 TEST PLANS AND PROCEDURES

A test and demonstration plan was produced early in the program for the Otis DPM winterization test and demonstration project and submitted as a deliverable under this particular program. It was written and released in November of 1978, and used as a planning/scheduling guide throughout the program. The test plan also provided the basis for establishing the test procedures and directing their scope and content. These two documents (test plans and test procedures) were used to execute the winterization test and demonstration program. Both documents were revised in October 1979, for implementation in the second winter season of operations under the test and demonstration project. The test

TEST DESCRIPTION	TEMPERATURE RANGE			
	<0°F	0°- 20°F	20°- 30°F	25°- 30°F
VEH. IMPACTED BY PRECIP.			D	C
COLD SOAK	A			
MAX. DEPTH SNOW 15 - 30%	D	D	A	
MAX. DEPTH SNOW <15%	B	B		
MAX. DEPTH SNOW > 30%			C	
CIRCULATING VEH. 15 - 30%	E	A	C	
CIRCULATING VEH. <15%	C	C		
CIRCULATING VEH. > 30%		E	B	
CIRCULATING VEH. - GLAZE ICE			E	A
CIRCULATING VEH. - RIME ICE				B

FIGURE 4-14. TEST PRIORITY MATRIX

plan provided the specific criteria developed by the Otis test team to achieve the test program objectives: 1) to demonstrate the capabilities of the Otis DPM system to operate reliably during severe winter weather conditions, such as cold temperatures and snow and ice accumulations; 2) to be able to recommend system configurations for winterized operations based on the demonstrations and experiences during the test and demonstration program; and 3) to determine the cost guidelines for providing the winterization of the Otis DPM system.

4.4.1 General Approach

The general approach used for the OTIS-TTD DPM system in the winterization demonstration are based on the vehicle/guideway and equipment configurations installed at the Duke University Medical Center and use of the existing OTIS-TTD test track guideway facility at Denver. The basic HOVAIR air suspension and LIM propulsion systems provide the vertical support, propulsion and service braking that do not depend on guideway traction. Otis air suspension vehicles can operate normally on guideways which are slippery and even ice-covered to some degree. Normal vehicle circulation during snow events will keep the guideway clear of snow if the guideway parapet walls are designed to allow the ejection of snow from the guideway surface as is the case at the OTIS-TTD Denver test track. Emergency braking integrity will be assured by heating the braking surface areas in the guideway. The installation and operating costs for this limited guideway heating will be a small portion of the potential total cost for heating an entire guideway surface. One purpose of the OTIS-TTD winterization program was to demonstrate the overall efficiency of this approach.

System elements such as power collectors and distribution rails, lateral suspension and guidance received critical consideration for winterized operation. Approaches as discussed in Section 4.2 included protective covers, special lubrications and heating for these particular elements as required. Snow removal from the guideway surfaces and hardware elements by use of maintenance snowplows and blowers of various types and the use of a vehicle-mounted snowplow was evaluated. The Denver area has cold weather of sufficient magnitude and duration to evaluate the operational characteristics of the DPM system hardware in snow and ice conditions.

4.4.2 Low Temperatures

System-level performance and vehicle hardware performance characteristics were evaluated under extreme low temperatures. Baseline data for energy consumption and operating cost comparisons were required for moderate temperature operations. Applicable vehicle subsystems, guideway and facility components, and system operation were evaluated during the following test sequences: 1) vehicle system/subsystem operation in moderate and low temperatures; and 2) overall system operation in moderate and low temperatures.

4.4.3 System Operation in Precipitations

System and subsystem performance was demonstrated in various precipitation conditions after the preliminary evaluation of these precipitation effects on vehicle and guideway hardware. The test vehicle was operated through the precipitations in the winterization test area simulating automatic vehicle service. Various types of precipitations were deposited at high rates of accumulation. If vehicle stoppage occurred due to the imposed winter conditions prior to the maximum specified depth of snow or precipitation to be deposited, the time to restore the system was measured and documented. The energy and other resources expended specifically to keep the system operational during the winter effects were also determined. If vehicle stoppage occurred within the winter test area, an analysis was conducted to determine the cause of the stoppage. Any potential winterization modifications that might help prevent this occurrence or improve the effects of conditions that lead up to the occurrence were investigated. All vehicle subsystems, guideway components, and normal system operation were evaluated during the following tests: 1) a preliminary evaluation of the vehicle components that were subject to winterization design alternatives; 2) performance and evaluation of potential guideway subsystem winterization modifications; and 3) system-level operations during severe winter precipitation conditions.

4.4.4 Precipitation Removal

This particular testing was conducted based on the accumulation of various types of precipitations on the guideway and related guideway hardware during a system shutdown. The use of the various removal techniques was demonstrated and evaluated. The OTIS-TTD DPM vehicle was evaluated in removing accumulations of precipitation with normal vehicle shrouds and debris guards in place and, further, while equipped with the specialized Otis winterization snowplow. The auxiliary maintenance vehicle was evaluated in removing accumulations of precipitation with both a snowplow and a snowblower. The effectiveness of the heater system was demonstrated on those guideway components where necessary to remove the accumulations of precipitation. The following test sequences were performed: the removal of snow accumulations of up to 16 inches with a water content of 15 to 30 percent; the removal of frozen rain of a maximum depth of 1 to 2 inches; and the demonstration of successful system operation after removal.

5. GUIDEWAY-RELATED TESTING

The center of the guideway surface contains the aluminum/steel reaction rail and is recessed into the guideway surface. On either side of the reaction rail are steel troweled concrete flying surfaces, each 24 inches wide. This surface is covered with a sealer to prevent deterioration and to improve the quality of the surface. Outboard of the flying surfaces are the emergency braking areas, 5 to 6 inches wide and sandblasted to a rough surface. The guidance and retention rails are mounted at the edges of the guideway slab approximately 4 to 6 inches above the guideway surface.

The DPM winterization test section has a test-track guidance rail on only one side and Duke guideway hardware on the other side. The Otis test-track guideway has no parapet walls but open post construction. The Duke hardware consists of 225 feet of aluminum guidance rail 6 inches above the guideway flying surface, approximately 60 feet of signal rail, and a 60-foot piece of guideway transmission line. This guideway transmission line is a far field cancelling helix wire inductive loop of the type pioneered, developed, and patented by OTIS-TTD.

The winterization modifications included heating of guideway components. This was performed by the resistance wire method in the braking surface, power rails, guidance/ground rail, and signal rail. The guideway concrete flying surfaces were covered with special coatings to mitigate ice adhesion. The power rails were provided with insulated covers in most areas where the rails were heated to determine the contribution to heating by these covers. Additional covers were tested in the early portions of the test program as a means to provide some weather protection for the power rails and signal rails. This preliminary testing was discontinued after some experimentation revealed significant complications in this effort with little discernible results.

5.1 SNOW AND ICE REMOVAL

Precipitations were classified in five different groups for purposes of winterization tests and demonstration evaluations. Snows of dry consistency were to be classified as one precipitation type if the moisture content was less than 15 percent by weight. Wet snows classified by a moisture content between 15 and 30 percent were described as a second snow type. Snowfalls with moisture contents in excess of 30 percent were described as slush. Two types of icing conditions were developed. The icing produced from freezing rains which would distribute evenly on cold surfaces and freeze was described as glaze ice. Rime ice was described as that icing condition produced naturally in sleets or in vehicle operations by water splashing and refreezing, producing rough ice surfaces.

The scenarios developed to simulate a worst-case condition for snow and ice removal from guideway and related equipment called for the advent of system down time. The guideway accumulations could potentially be as high as 16 inches of snowfall in the dry and wet snow classifications. This snow accumulation was to be removed from the guideway with a determination made as to the costs in energy and resources consumed to restore system operation. The third snow type, described as slush, was to be removed in accumulations of up to 5 inches. The icing of the guideway was the equivalent of up to 1 inch of off-guideway accumulation of freezing rain, representing glaze ice, or the accumulation of up to 2 inches of rime icing conditions. The OTIS-TTD test scenario calling for removal of these snow and ice accumulations from the guideway was based on three different approaches. The first approach called for a normal winterized vehicle to operate through the affected area. This was attempted in dry snows with accumulations of up to 12 inches and with ice accumulations on the guideway. The second approach was to operate the normal winterized OTIS-TTD vehicle with the attachment of the specially-designed Otis snowplow. This snowplow was attached to the front of the chassis and interfaced the guideway surface guidance rails and power distribution rails. The third approach was the removal of the precipitation accumulations utilizing the maintenance equipment (an 18-horsepower garden tractor equipped with either snowplow blade or snowblower). Some data points were achieved utilizing a small (walk-behind) 22-inch snowblower unit. This third approach also included the evaluation of the amount and extent of hand-cleaning operations required.

5.1.1 Snow and Ice Removal with Normal Vehicle Operations

The OTIS-TTD vehicle, as configured for winterization testing and demonstration, included shrouds and covers to materially extend the vehicle operating parameters during severe weather conditions and to protect vehicle components. The test vehicle was used for the removal of dry snows with a moisture content of less than 15 percent and operation with ice accumulations on the guideway. The vehicle was operated manually by an on-board operator. The snow and ice accumulations were placed in the winterization test section of the OTIS-TTD test-track guideway to the depth determined for the test procedure. The vehicle was then operated through the test section area demonstrating the removal of the precipitations to the extent required to achieve system operations in an automatic mode.

Of specific interest in this test were the shroud and debris guard installations on the ends of the vehicle chassis. The debris guard consists of a V-shaped rubber-tipped wiping assembly that is installed on the leading edge and trailing edge of the vehicle chassis and interfaces the guideway flying surface and LIM reaction rail. The rubber edge of the debris guard flexes, allowing the vehicle to sit on its brake skid pads while the vehicle air suspension is not operating. When the vehicle is flying, the rubber edge conforms to the guideway flying surfaces and LIM secondary. This debris guard removes any minor accumulations of snow and ice that might reduce the efficiency of the vertical air suspension system. Debris guards are a normal installation on Otis vehicles and additionally extend the vehicle operating capabilities in severe winter climatic conditions. Vehicles are equipped with fiberglass-reinforced shrouds around the ends of the vehicle chassis. The shrouds in a normal vehicle configuration perform the following functions:

a. provide an aesthetic closure of the vehicle chassis,

b. provide an emergency egress from the escape window, and

c. provide weather closeout protection for the vehicle air intakes.

Vehicle bumpers and couplings are included within this vehicle shroud installation. For winterization tests and demonstrations, a standard vehicle shroud was used with winterization modifications. The modifications prevent guideway snow accumulations from getting behind this shroud enclosure.

The OTIS-TTD Duke test vehicle was used several times to clear snowfalls from the guideway without vehicular modifications or addition of any snow removal equipment. A 2- to 3-inch heavy wet snow, which turned to slush on a warm guideway, was successfully cleared by the vehicle. The buildup of snow typically forms a natural Vee shape in front of the vehicle shroud, directing the additional snow accumulations to the sides and off the guideway surface. Test runs have shown that heavy wet snowfalls should be removed before freezing. In another snow removal test sequence in the 1978-1979 season, an average 5.3-inch snowfall with a water content of 16 percent, was removed without incident by a normally-equipped OTIS-TTD Duke test vehicle.

On February 9, 1980, natural snow accumulations of 5 to 6 inches with drifts of up to 12.5 inches on the guideway were cleared manually by operating the Otis test vehicle through the snow accumulations. The moisture content of the snow was 11 to 12 percent with a temperature of 3°F. After 45 minutes with brake surface heaters energized, an emergency brake stop was made with normal braking rates, and automatic system operations were begun without incident.

This particular snow fall actually started the previous day during vehicle circulation, and operations were maintained during the snowfall until the system was shutdown with resultant guideway accumulations occurring overnight. Figure 5-1 shows the test vehicle during snow removal.

On the 29th of February, 1980, the vehicle was operated in man-made freezing rain conditions with 0.5 inch of ice on the guideway. An overnight natural snowfall of 2 to 4 inches (12 to 15 percent moisture content) fell on the guideway on top of the ice accumulations that were produced in the previous day's testing. The freezing conditions associated with the snowfall produced snow and ice accumulations in the power rails. Where heaters were not provided, melting and scraping of the rails were required prior to operations. The Otis test vehicle in the normal configuration was operated through the winterization test section and successfully removed the snow accumulations on the iced surface.

Ice removal capabilities were demonstrated on eight different occasions during the 1979-1980 portion of the OTIS-TTD winterization test and demonstration program. The ice accumulations were produced by spraying water on the guideway surfaces and related hardware and allowing this to freeze. The OTIS-TTD test vehicle was operated through this iced portion of guideway under full automatic control with debris guards and shrouds in place (normal configuration). The guideway heating equipment was activated on the brake surfaces, power rails, guidance/ground rail, and signal rail prior to operations. In all cases, no operational difficulties were ever encountered in operating the Otis test vehicle through these particular conditions. The off-guideway accumulations of freezing rain or sleet usually totaled in excess of 1 inch, but the total accumulation that remained on the reaction rail and flying surfaces never exceed 0.75 inch. No attempt was made to remove this remaining ice accumulation. When daytime temperatures rose above freezing, the ice accumulation on the guideway was removed completely by the vehicle during automatic

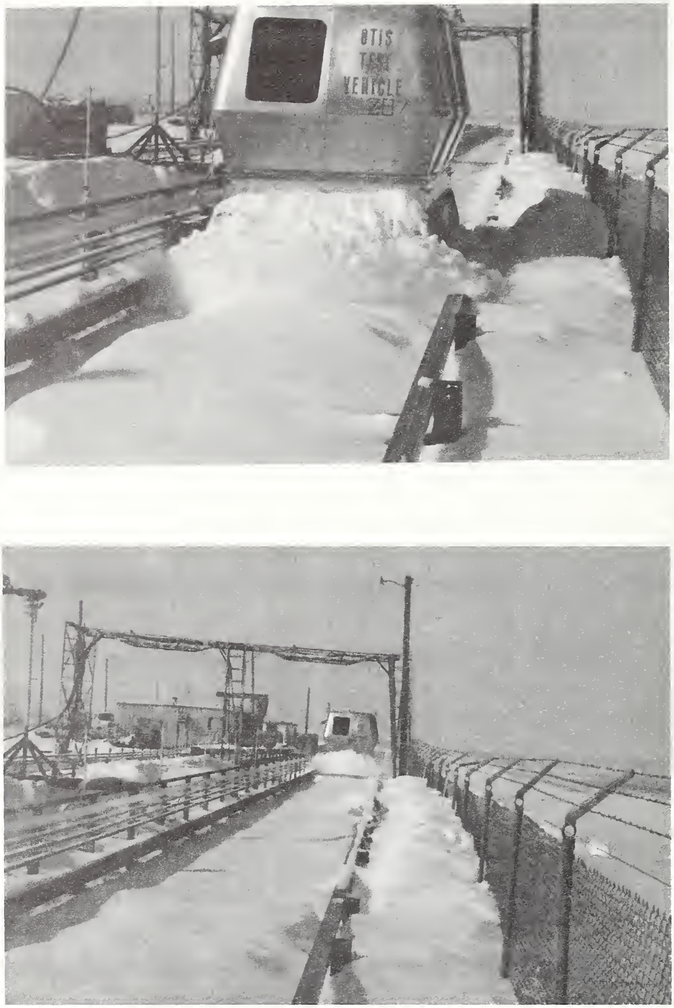


FIGURE 5-1. NORMAL VEHICLE SNOW REMOVAL

operations, leaving the guideway clear and dry. The circulation of the vehicle in the automatic mode through these icing conditions resulted in increases in thrust that were barely measureable with the test equipment. Figure 5-2 shows a normal vehicle operating on ice-covered guideways.

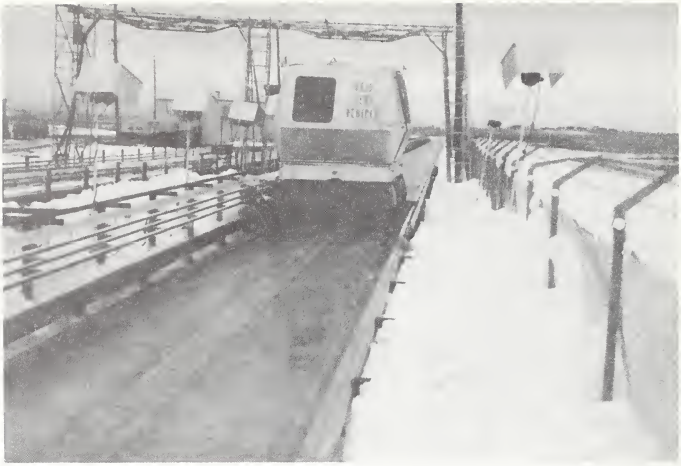
5.1.2 Snow and Ice Removal with Test Vehicle Snowplow Operations

The OTIS-TTD winterization test vehicle was equipped with a V-shaped snowplow mounted to the leading edge of the vehicle chassis. This snowplow was designed and fabricated by Otis to remove heavy accumulations of snow on the guideway. The plow was equipped with skids which contacted the guideway flying surface to maintain the interface relationship between the plow and the top of the guideway surface. The plow was provided with guidance stop blocks interfacing the guidance rails to prevent the wings of the plow from interfering with guideway-mounted equipment. The snowplow was fabricated in early 1979, but was not tested in snow accumulations that winter season due to the advent of warmer weather conditions.

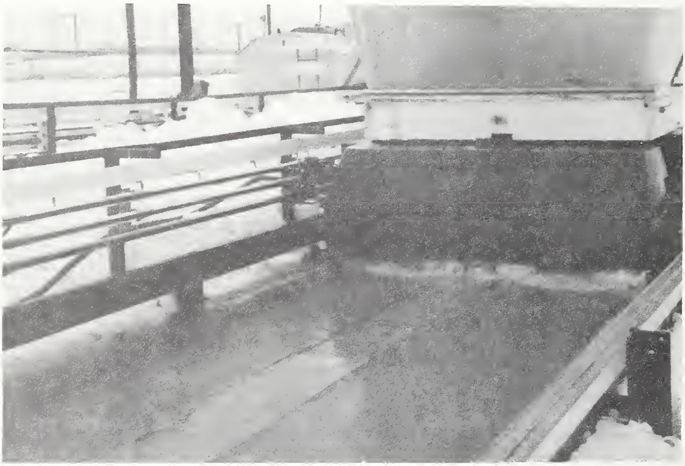
On six different test days the snowplow was utilized to remove man-made snows with moisture contents of 20 to 40 percent and accumulated depths of 6 to 25 inches. It became evident during these tests that man-made snow could not be produced in sufficient quantities with moisture contents of less than 20 percent.

On the 7th of January, 1980, the snowplow was run into an accumulation of 1 to 3 inches of heavy wet crusty snow. The plow rode up on top of the hard snow and failed to remove the accumulation. The snowplow was taken off the vehicle and modified to improve its performance. (See Figure 5-3.)

On the 21st of January, snow was produced on the guideway over approximately 6 hours to depths of 8 and 9 inches over the test section, with a moisture content of 25 to 27 percent. The plow, moving 20 fps, removed the snow accumulations from the guideway surface by lifting the snow up off the guideway out the wings 3 to 5 feet beyond the edge of the guideway structure. The



TEST VEHICLE OPERATING IN ICE CONDITIONS



CLOSE-UP SHOWING THE ACTION OF THE DEBRIS GUARD

FIGURE 5-2. NORMAL VEHICLE OPERATIONS IN ICE

FIRST VEHICLE SNOWPLOW RUN INTO 3 INCHES OF SNOW

PLOW RIDES UP ON SNOW ACCUMULATION AND STOPS

FIGURE 5-3. TEST VEHICLE SNOWPLOW RUN

operation of the snowplow left a very clean guideway surface. After the snow was removed from the guideway, the emergency brake surface heaters were turned on. Within an hour after snow removal operations began, normal emergency brake tests were performed and automatic operations were performed. Figure 5-4 shows this snow removal.

After the successful snowplow operations it was decided to produce heavier accumulations of snow. On January 22nd, snowmaking operations continued until accumulations on the guideway measured from a low of 8.5 inches to a maximum depth of 25 inches. The moisture content was measured at four different locations within the test area and ranged from 36 to 45 percent. Although the accumulation and moisture content were far in excess of the test objective (16 inches at 30 percent), the vehicle with the snowplow was run into the snow accumulations. This particular snow was described as igloo-type snow, very blocky and chunky, extremely hard. If this snow could be cleared, any snow condition imaginable could be handled by the vehicle plow. The vehicle entered the snow area at 20 fps and removed snow for approximately 75 feet. Power collector contact was lost from the rails resulting in a vehicle power distribution fault. The vehicle was again operated into the snow accumulations and removed 35 feet of snowfall, was backed out and on a third run, the remainder of the snow accumulations were removed. Figure 5-5 shows this snow removal. The vehicle snowplow operation was extremely successful in clearing the guideway surface and removing the snow accumulations of this particular magnitude and density. It was evident after this particular run that the snowplow would operate more efficiently and with better results at higher velocities. In addition, it was felt that improvements could be made to the snow plow to reduce the amount of snow left in front of the guidance rails and power rails after plowing. A modified wing was added to the snowplow to clear the snow accumulations to within approximately 1 inch of the power rails.

VEHICLE SNOWPLOW OPERATIONS IN 10 INCHES OF SNOW

AFTER CLEARING, NOTE CLEAN GUIDEWAY
ALLOWING RESUMPTION OF AUTOMATIC OPERATIONS

FIGURE 5-4. VEHICLE SNOWPLOW OPERATIONS

VEHICLE BLASTING THROUGH WET SNOW ON LAST RUN

EXCELLENT GUIDEWAY CONDITION AFTER THREE RUNS

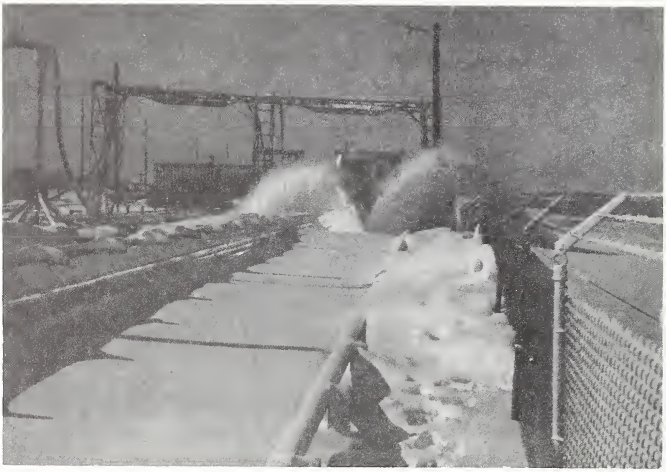
FIGURE 5-5. VEHICLE SNOW REMOVAL OPERATIONS

On January 30th, man-made snow was produced for approximately 6 hours. High relative humidities (97 percent) produced snow moisture contents (35 percent) that were again above those specified in the test program with snow accumulations from 12 to 18 inches on the guideway. The vehicle with a modification attached to the right-hand wing of the snowplow was operated into the accumulated snow. Four runs were made at 20 fps into the snow accumulations, backing out of the snow bank each time, until the test section was cleared. Figure 5-6 shows this snow removal. An inspection of the guideway after the snowplow operation indicated that additional modifications to the snowplow could improve its operation by minimizing snow spillage from the plow blade and wing into the vehicle power collection mechanism. The general guideway condition after plowing was very clean of any snow and/or ice buildups.

Dynamic evidence using 35-mm photographs and video tape shows that an operating speed of 20 fps is below that considered to be desirable, but for test purposes, the test-track speed limit remained at 20 fps. For deployment, the vehicle power collectors should be relocated to the opposite end of the vehicle away from the snow plow, with the addition of power collector shrouds.

Snowmaking operations on the 11th of February produced accumulations of 9 to 10 inches. A moisture content of 20 to 40 percent with warming temperatures prevented further snow production. The vehicle was operated into the snow accumulation on two runs, totally removing the snow coverage in the winterization test section. Vehicle stoppage after plowing resulted from a component failure not related to the winter conditions. The condition of the guideway after plowing was improved over the previous run and allowed the immediate resumption of automatic vehicle operations.

Another day of snow production on February 15th resulted in snow depths varying from 12 to 15 inches over 150 feet, with a moisture content of 25 to 36 percent. The vehicle cleared the



JANUARY 30th, SNOWPLOW RUN AGAIN IN WET SNOW 21 INCHES DEEP

TEST VEHICLE SLOWED PUSHING DEEPEST SNOWS WITH PLOW

FIGURE 5-6. SNOWPLOW OPERATIONS

test section in three runs at 20 fps. The results were not different from the previous runs and some difficulty resulted by disturbance to power collection mechanisms. The snow accumulations that were coming off the snowplow wing on the power distribution side of the guideway were still causing problems for the power collection assembly which was located just to the aft and below the snowplow. In this particular case, when enough snow had fallen into the power collector mechanism, it eventually forced one of the brushes to leave the power distribution rails causing a system imbalance and a ground fault. It is clear that in vehicle snowplow operations, the snowplow wing that interfaces the side of the guideway and the power rails needs further modification. The snowplow as configured does an excellent job of clearing the guideway surface, power rails, guidance and retention rails of snow, but the snow needs to be dispersed over and outside the power distribution rails and the vehicle-mounted power collector assembly. Snowplow improvements and operating speeds above 20 fps will provide the desired results in this snow dispersal, along with requiring the power collection mechanism to be relocated to the opposite end of the vehicle from the plow.

5.1.3 Snow and Ice Removal with Maintenance-Vehicle Operations

During the 1978-1979 winter season, the maintenance vehicle (an 18-hp tractor) equipped with either a snow blade or a snowblower, and a walk-behind snowblower were used to clear both man-made and natural snows from the guideway. The maintenance vehicle with front-mounted snowplow blade was operated in several natural snowfalls during the first winter season. Snows of 3 to 5 inches deep and with a water content of up to 30 percent can be successfully cleared at rates of 3000 to 4000 lane-feet/hr using the plowing equipment with the following considerations: the guideway structure must have open sides with no guidance curb or other structure within 8 inches of the guideway flying surface along the sides; and the wet snows or slush must not be allowed to freeze on a guideway surface before removal. Figure 5-7 shows the maintenance vehicle.

A 26-inch walk-behind, two-stage, 8-hp snowblower was used to remove snow from several selected areas of the guideway resulting from a natural snowfall of 5 to 6 inches with a water content of 16 percent. This removal method worked as well as the maintenance vehicle with plow attachment with the following considerations.

This particular snowblower does not clean any closer than 1 to 1.5 inches of the sides of the guideway or guidance curbs and leaves approximately 0.75 inch of snow residue on the guideway surface. It is possible to operate the vehicle through this type of snow residue on the guideway, but it adds some delay in returning the system to normal automatic operations after the manual maintenance snow cleaning. Several years of experience using this type of equipment has shown that the maintenance and upkeep requirements remain fairly high and relief operators are required to clear a given length of guideway. Snow accumulations of 10 to 12 inches can be removed provided the moisture content does not exceed 25 percent.

The maintenance vehicle also mounts a 42-inch single-stage snow thrower that works well in clearing the guideway surface under most snow accumulation conditions. Energy consumption with this piece of equipment averaged one gallon of gasoline per hour of operation regardless of the amount or type of snow. The following types of snow were successfully removed from the OTIS-TTD test-track guideway using the maintenance vehicle and the 42-inch snowblower:

1. Several 3- to 5-inch snowfalls with water contents varying between 5 and 20 percent.

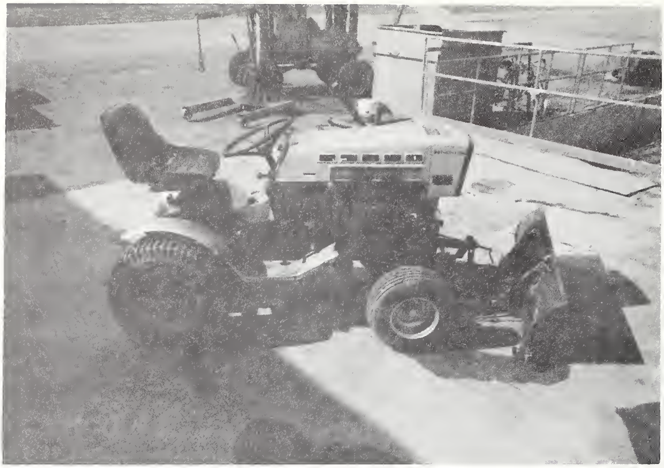
2. A 3- to 4-inch snowfall of heavy wet snow that turned to slush on a warm guideway. In this application, some difficulty was encountered with the discharge chute plugging with the heavy wet snow and the snowblower being

unable to throw the heavy snow far enough to clear all of the guideway apparatus. Under these conditions, the plow blade would be a better removal tool.

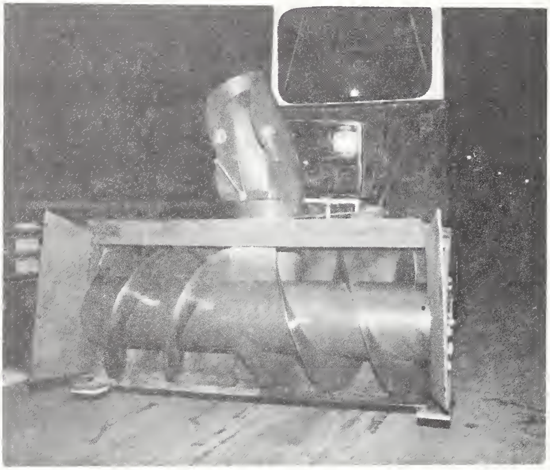
3. A 6-inch snowfall with a water content of 16 percent and drifts of up to 24 inches was removed from 2500 feet of guideway in approximately 45 minutes.

4. An 8- to 10-inch snowfall with a water content of 25 percent and fairly consistent drifts of over 24 inches was only partially removed by the use of the maintenance vehicle with snowblower. When the average depth of this drifted wet snow exceeded 15 inches, the tractor did not have enough ground traction to push the blower assembly into the compacted snow drifts.

The maintenance vehicle with the snowblower attachment will clear the guideway in less time than the other methods used, with times for clearing 2 to 6 inches of snowfall averaging 2000 to 5000 lane-feet/hr. Dry snow (less than 20 percent water content) of up to 18 inches in depth can be removed easily from the guideway. Heavier snows (up to 30 percent water content) can be removed in depths of up to 10 inches, above which the unit becomes traction-limited. Also, in these heavy wet snows, difficulties are encountered with clogging in the discharge-chute area. For the 1980 winter season, the maintenance vehicle 42-inch snowblower unit was modified to improve snow removal performance. The enclosure of the snowblower auger was modified to reduce the frontal area that the snowblower presented to the snow accumulations. This was accomplished by introducing sharply-angled side plates to remove and guide snow accumulations into the auger. In addition, the top edge of the snowblower auger enclosure was modified with a sharply-angled plate to guide the snow accumulations that were above 15 inches into the snowblower auger. These plates were painted with a friction-reducing paint similar to that used on snowplow blades. Figure 5-7 shows this modified snowblower attachment.



OTIS-TTD MAINTENANCE VEHICLE WITH PLOW ATTACHMENT



OTIS-TTD MAINTENANCE VEHICLE WITH MODIFIED
42-INCH SNOWBLOWER AND ENCLOSED CAB

FIGURE 5-7. SNOW REMOVAL/MAINTENANCE VEHICLE

Early in the 1979-1980 winter season test program, a significant winter storm event occurred on the 20th and 21st of November, with heavy snow accumulations, high winds, and snowfall rates at times exceeding 3 inches per hour. These weather conditions completely closed down the surrounding area, and the highways to the test site location were closed for 6 days. On the 21st of November, an effort was made to get to the test track and a crew succeeded in walking to the test site to get some information from this particular severe storm event. The winds were still gusting at or above 60 mph and snow was still falling. The maintenance vehicle with the front-mounted 42-inch snowblower unit was operated in heavy drifts averaging between 2 and 3 feet in depth over the entire guideway surface. One hour of operation with the snowblower effectively cleared approximately 200 feet of guideway. As the snow was cleared, the high winds drifted the snow back in place and a portion of the time during that 1 hour of operation was required to remove these additional drifted accumulations. With snow accumulations drifted to these extreme levels, the tractor became traction-limited on the guideway surfaces. The result was having to run the snowblower unit again and again into the drifted snowbank to remove any snow from the guideway.

Further access to the test site was not achieved until mid-morning of the 26th of November, when the roads were finally opened and a full crew arrived at the test site. During this lapse of approxiamtely 5 days and with the advent of warmer weather, the snow accumulations which had drifted to 4 and 5 feet deep on the test guideway and the roads were melted and reduced to approximately 70 percent of those accumulated depths. This, of course, significantly increased the moisture content in the drifted snows, making them very difficult to remove. The next 2 days were spent removing the drifted snow accumulations from the guideway, station and maintenance areas by hand. The snowblower was used to throw the snow off the guideway surfaces, but had to be assisted by hand operations. Snow fencing should be installed for at-grade guideway installations to reduce the drifting of snowfalls on the guideway. Figure 5-8 shows the snow accumulations at the test facility during this particular storm event.

5.2 ELECTRICALLY HEATING SELECTED COMPONENTS

Before the actual test and demonstration program began, it was OTIS-TTD's opinion, based on previous experience with winter operations, that, as a minimum, certain guideway components would require supplemental heating to ensure operational capability. The items identified as requiring heating were the power distribution rails, the signal rail, the ground rail and the guideway emergency brake surfaces. With these particular elements heated to prevent freezing accumulations of ice and snow, normal automatic vehicle operations could be conducted during precipitation conditions with temperatures below freezing. Initially, the heating power requirements were based upon levels that were established in existing industry installations. The power level requirements for heating the various individual guideway components have not been extensively evaluated in the industry at this time. OTIS-TTD's approach was to select the nominal heating power levels as necessitated by the winter conditions and provide a heating control and distribution system that would allow the selection of various heating power levels, and further, to determine an optimum heating power level considering both the reliability of the operations during extreme winter conditions and the costs required to provide heating for the various guideway components.

5.2.1 <u>Power and Ground Rails</u>

For the winterization test and demonstration program, approximately 230 feet of the three-rail power distribution system at the OTIS-TTD test track had resistance wire heating elements installed. The heated portion of the power rails was located within the winterization test section. The Duke guidance and ground rail that was installed in the winterization test section was heated by resistance wire over a length of 90 feet. The

WINTERIZATION TEST ENCLOSURE
DURING BLIZZARD OF 11-21-79

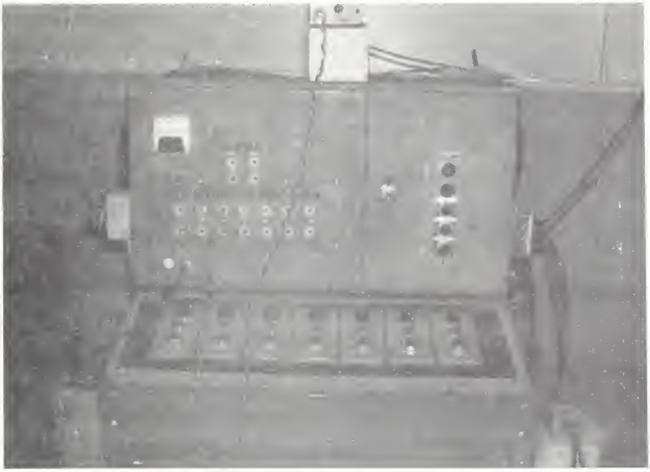
OTIS-TTD TEST TRACK GUIDEWAY
WITH VEHICLES DURING BLIZZARD

FIGURE 5-8. OTIS TEST TRACK DURING BLIZZARD OF 11-21-79 resistance heating wire was rated at 15 watts/ft with a DC resistance of 0.08816 ohms/ft. The Howell power rail has notches in the front edges of the rail to allow the wire installation. In some areas, plastic rail covers were installed to evaluate the contribution of these covers in reducing the heating requirements. (See Figure 5-9).

The ground rail also has provisions made for the easy installation of resistance heating wire. The same heating wire used in the power rails was installed in the ground rail. In the ground rail installation, two wires were installed, one on the top and one on the bottom, which provided up to 30 watts/ft of heating capability. The ground rails were not provided with protective covers, but provisions were made for evaluating the effects of insulations and potential cover candidates later in the program. The resistance wires were supplied through an electrically-isolated power branch circuit and autotransformer allowing the selection of the operating voltage on the various subcircuits to optimize the power levels required.

The initial heating power level established for the power rails was 11.5 watts/ft. During the test program, this level was reduced to approximately 10.4 watts/ft and then further to 8.8 watts/ft. The major test program operations were conducted using the initial power level of 11.5 watts/ft. This provided adequate heating of the power rails during all of the winter conditions experienced during the test program.

The ground rail was operated initially at 33 watts/ft. This level was reduced later in the program to 28.5 watts/ft and further to 24.5 watts/ft. The performance of the heaters in the ground rail without any insulation being added was more than adequate at the initial 33 watts/ft. The grounding system achieved excellent results during the winter conditions throughout the program using these power levels. These power levels proved to be significantly higher than those required. Typical stablized temperatures measured during one test reached 70° to 80°F on the ground rail surface with starting ambient temperatures



WINTERIZATION GUIDEWAY HEATING CONTROL
AND MEASUREMENT CONSOLE

WINTERIZATION TEST AREA POWER DISTRIBUTION RAILS
WITH COVERS AND TEMPERATURE SENSORS

FIGURE 5-9. GUIDEWAY HEATING CONTROL CONSOLE
AND POWER DISTRIBUTION RAILS

of $18^{o}F$ and winds from 11 to 18 mph. In later tests with reduced power levels at 28.5 watts/ft, the measured average surface temperature of the ground/guidance rail reached $66^{o}F$ starting with ambient temperatures of $23^{o}F$, and at 24.5 watts/ft the resulting average ground/guidance rail surface temperature was $52^{o}F$ starting with ambient temperatures of $27^{o}F$. It is apparent that the use of these lower power levels would produce successful system operations under the conditions tested for at the OTIS-TTD Denver test site. Adequate assurance that high winds would not detrimentally affect the heating capabilities of these rails can be provided by a cover or insulation material to prevent heat loss during wind conditions. The temperature-rise curves on both the power rails and ground rails using this particular heating method were rapid, with the rails typically reaching 70 to 75 percent of their stabilized operating temperature in 30 minutes. The temperature rise to an equilibrium temperature was achieved after approximately 1 hour to 1 hour and 30 minutes. Some typical temperature-vs.-time curves are shown in Figures 5-10 and 5-11 for the Howell power rails. Figures 5-12 and 5-13 show the temperature-vs.-time characteristics of the OTIS-TTD Duke ground/guidance rails. Figure 5-14 shows the temperature sensor installation. Figure 5-15 is a table showing the power levels on the various guideway component heater circuits and corresponding operating voltages and currents during three specific test evaluations.

Small differences in the rail temperatures were noted with and without the insultative covers on the power distribution rails. Where the winds caused rail temperatures to drop, small improvement was attributed to the ability of these covers to retain the heat within the rails. Power rail insulative covers may provide some protective contribution in winds above 20 mph. Heated power and ground rails provided reliable operations in all winter conditions tested after 20 to 30 minutes of warm-up time. A specific incident of power rail icing or related failure never occurred on the heated rails in the operating system.

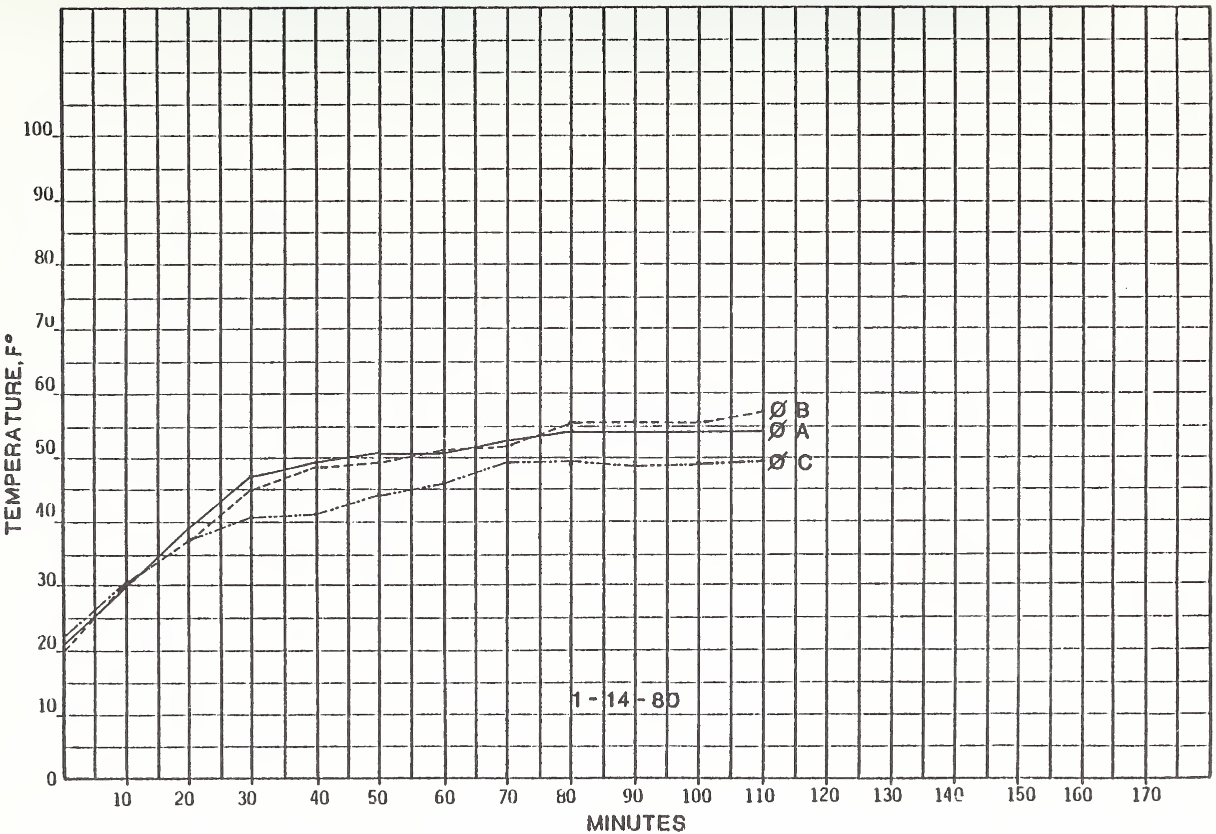


FIGURE 5-10. POWER RAIL TEMPERATURES AT 11.5 WATTS/FT

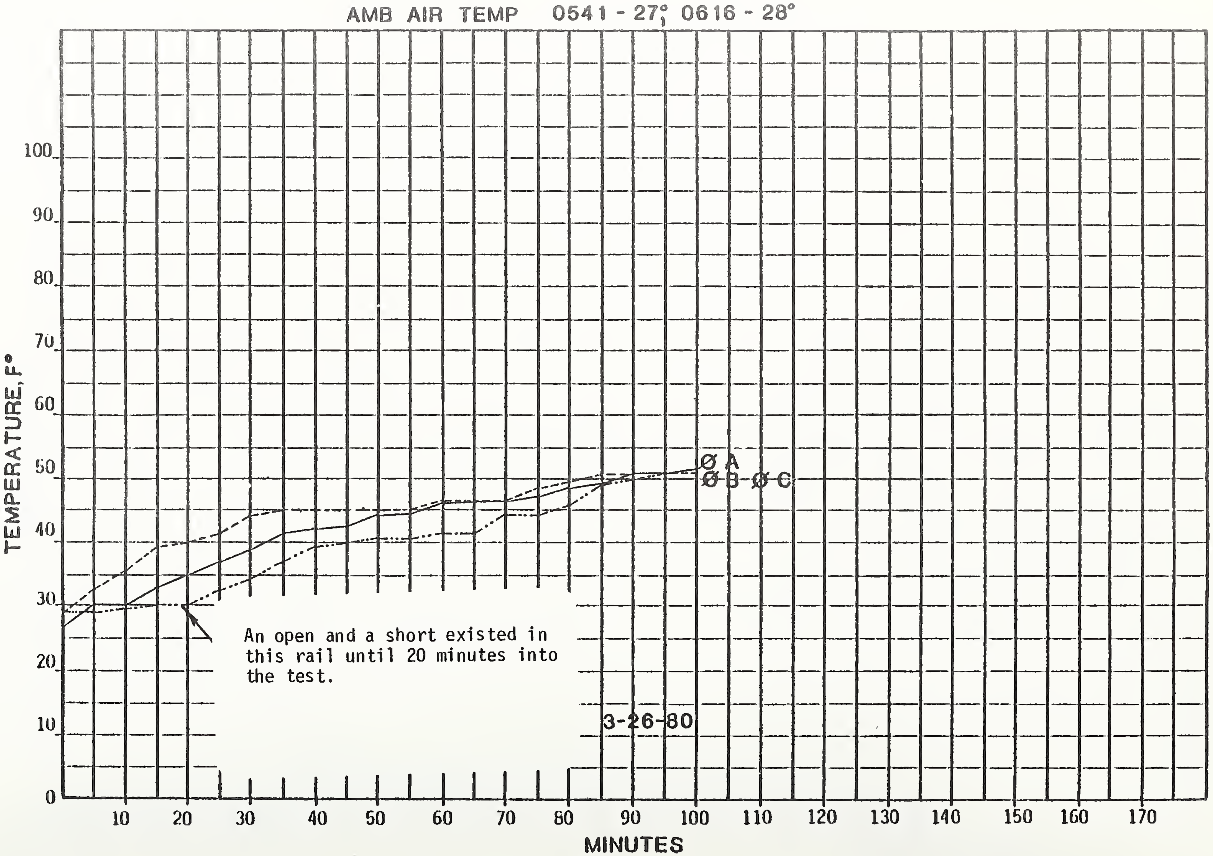


FIGURE 5-11. POWER RAIL TEMPERATURES AT 8.8 WATTS/FT

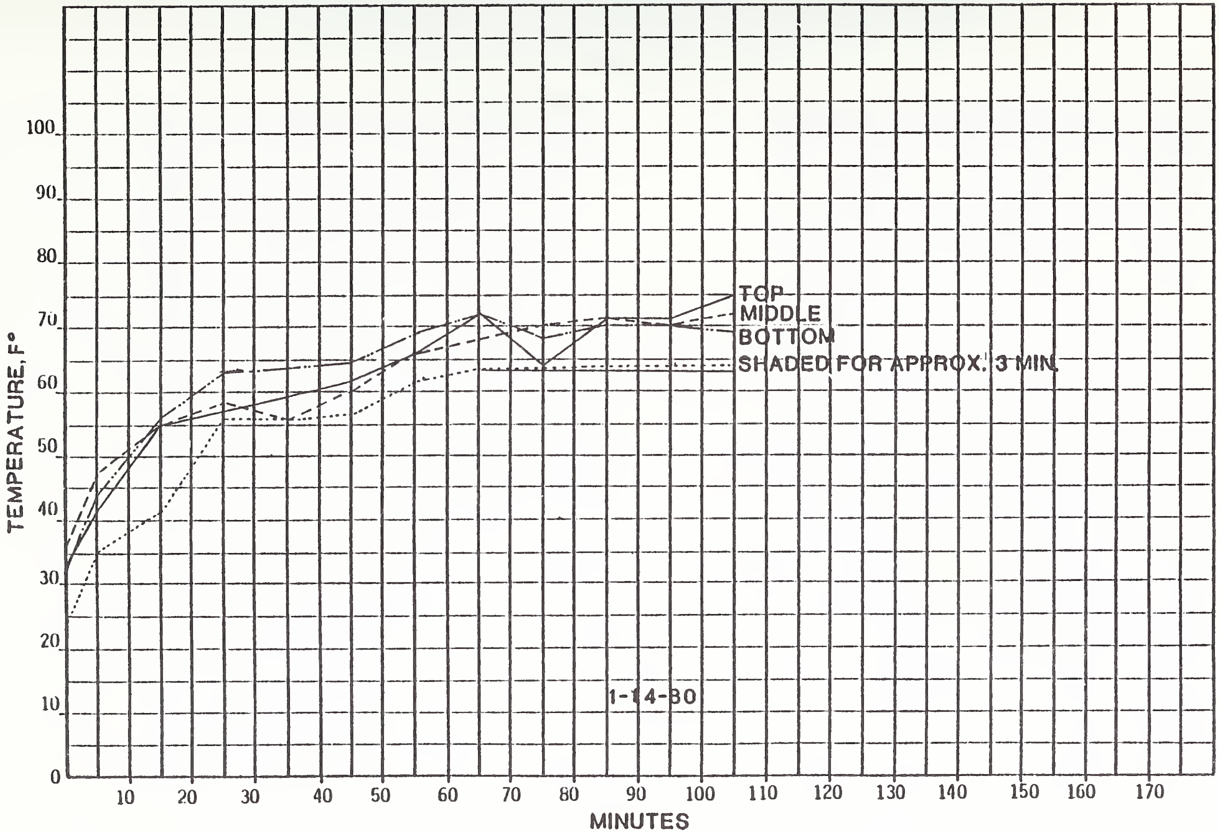


FIGURE 5-12. GROUND RAIL TEMPERATURES AT 33 WATTS/FT

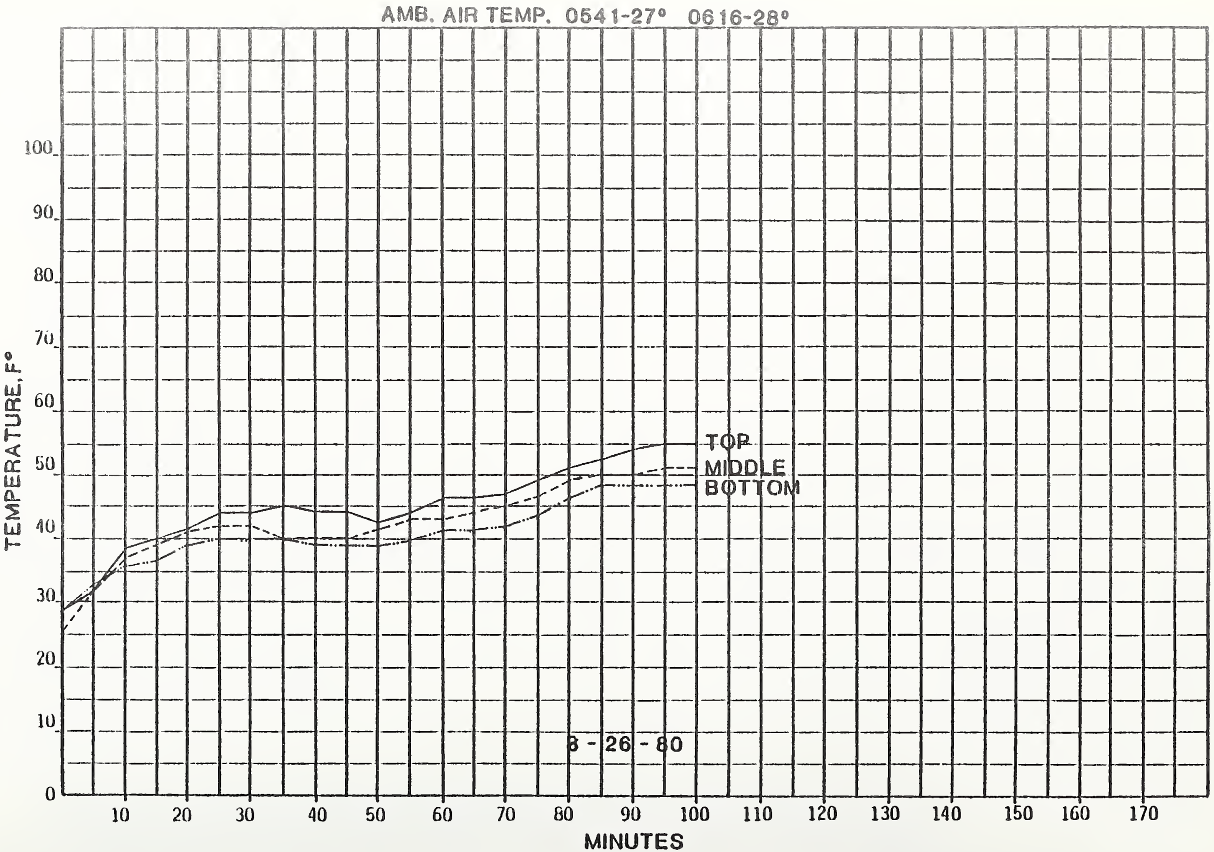


FIGURE 5-13. GROUND RAIL TEMPERATURES AT 24.8 WATTS/FT

TEMPERATURE SENSOR INSTALLATION ON PHASE B POWER RAIL

TEMPERATURE SENSORS INSTALLED ON DUKE (DPM)
GROUND/GUIDANCE RAIL

FIGURE 5-14. GUIDEWAY HEATING TEMPERATURE SENSORS

CIRCUIT	1-14-80 NORMAL POWER			3-24-80 REDUCED POWER			3-26-80 REDUCED POWER		
	VOLTS	AMPS	WATTS	VOLTS	AMPS	WATTS	VOLTS	AMPS	WATTS
POWER RAIL ØA #B	232	11.75	2726	205	12.05	2470	187	10.95	2048
PER ft			11.87			10.76			8.92
POWER RAIL ØB #C	228	11.35	2588	197	11.55	2275	184	10.75	1978
PER ft			11.28			9.91			8.62
POWER RAIL ØC #D	230	11.5	2645	200	12.0	2400	186	10.85	2018
PER ft			11.53			10.46			8.79
SIGNAL RAIL #E	115	15.04	1728	96	13.64	1309	93	12.8	1190
PER ft			21.09			15.96			14.51
GROUND RAIL #F	215	13.7	2945	200	12.75	2550	186	11.85	2205
PER ft			33.1			28.65			24.77
BRAKE SURFACE #G	212	23.7	8702	200	22.1	7655	190	20.2	6648
PER ft			29.0			25.52			22.16
POWER RAIL POWER AVE/ft			11.56			10.37			8.77

FIGURE 5-15. GUIDEWAY HEATING POWER LEVELS

The baseline of some unheated rails at the test site provided a comparison of the need of heating during winter conditions. It was readily apparent that in winter conditions, except for a few specific and non-severe incidents, rails without heaters were completely unsuitable for winter operations.

During the operation of the test and demonstration program, the guideway components that were heated by the resistance wire methods experienced some failures attributable to the installation techniques. Specific recommendations would be that wires with solid conductors should be considered and wires with better insulation systems need to be installed with care to provide sufficient weather protection and strain relief.

5.2.2 Signal Rail

A signal rail installation was provided as part of the Duke hardware which was installed in the winterization test section. This rail also had resistance heating wires installed. This installation was very similar to the heating provided in the power distribution rails. The initial heating level of this rail was found to be considerably higher than required for this installation. The initial heating power level was 21 watts/ft and heated the signal rail to an equilibrium temperature of 90°F. The power level in this rail was later reduced to 16 watts/ft and then to 14.5 watts/ft. It appears that the 11.5 watts/ft which was tested on the power distribution rails as being too high, would be an ideal recommended heating level because of the lower voltages used on the signal rail. Figure 5-16 shows the temperature rise on this rail.

Operation of the vehicle, during winter conditions, within 10 to 15 minutes after the signal rail heaters were energized could produce marginal conditions that would result in some signal losses. These losses may or may not contribute to vehicle shutdowns. With recommended signal rail heating levels, winter conditions which would affect signal rails could be corrected in 15 to 20 minutes, allowing normal system operations.

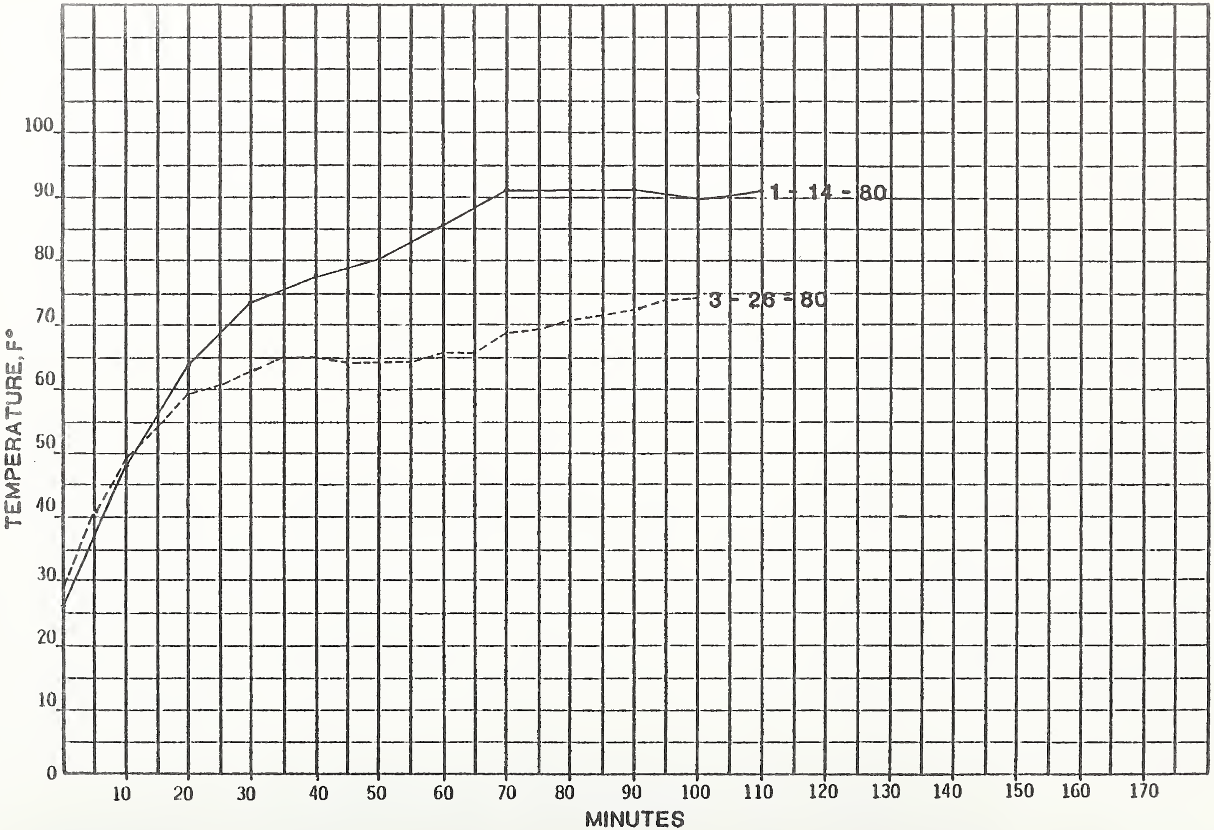


FIGURE 5-16. SIGNAL RAIL TEMPERATURES

5.2.3 Emergency Brake Surfaces

The sandblasted-concrete emergency brake surface, located on the outboard edges of the guideway slab and approximately 6 inches in width, needs to be maintained clear of ice and snow accumulations. Otis Elevator's experience in operating under winter conditions indicates a need to provide heating for these particular surfaces. The resistance wire heating method was also used to heat the concrete emergency brake surfaces. Two slots approximately 1/8 inch wide, 3/4 inch deep and 150 feet long were cut in each brake surface. Heating wire was installed in these slots in the braking surfaces. The slots were located 2.25 inches apart and centered in the brake surface areas. The wire was sealed in the slots using a silica sand/epoxy system which provided a surface texture equivalent to that of the sand-blasted concrete.

Initially, these heaters were operated at a power level of 29 watts/ft, or 58 watts/ft/lane. This power level was used throughout the test program and provided sufficient heat to maintain the integrity of the emergency braking surfaces under all winter operating conditions. The installation techniques proved to be successful and over the 2-year period no heating system failures were encountered. Figure 5-17 shows the location of the emergency brake surfaces, the slots in the concrete for the resistance wire heaters, and the location of the temperature sensors used to monitor the emergency brake surface temperatures.

Temperature monitoring of the emergency brake surfaces showed a temperature rise that averaged approximately 25^{o}F above ambient and reached an equilibrium temperature approximately 2 hours after the heaters were energized. The condition of the emergency brake surface while energized showed that within 45 minutes after start-up, the surface became wet and frozen accumulations were melted and that emergency braking rates were normal. The temperature-rise curves for the emergency brake surface are represented in Figures 5-18 and 5-19, showing the relationship of

WINTERIZATION TEST AREA
SOUTHSIDE EMERGENCY BRAKE SURFACE

BRAKE SURFACE SHOWING HEATING
WIRE SLOTS AND TEMPERATURE SENSORS

FIGURE 5-17. EMERGENCY BRAKE SURFACE

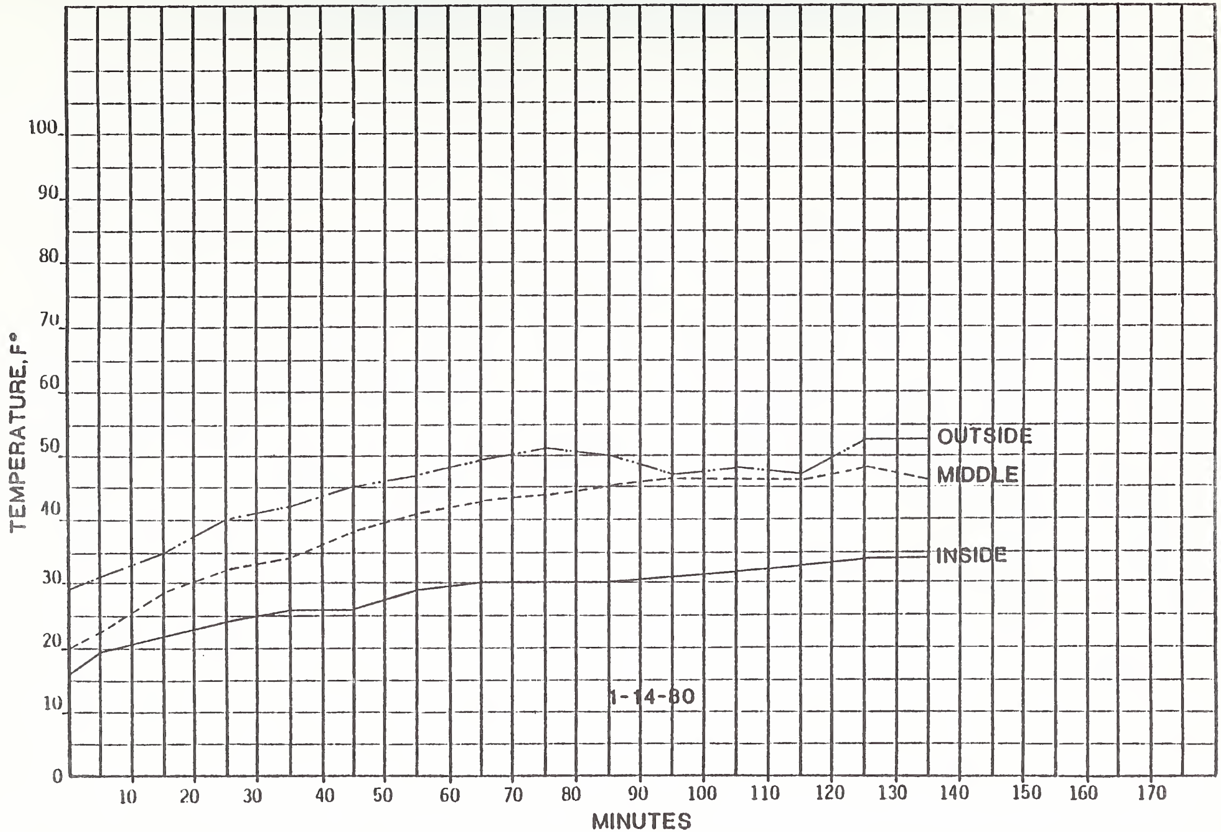


FIGURE 5-18. EMERGENCY BRAKE SURFACE TEMPERATURES AT 29 WATTS/FT

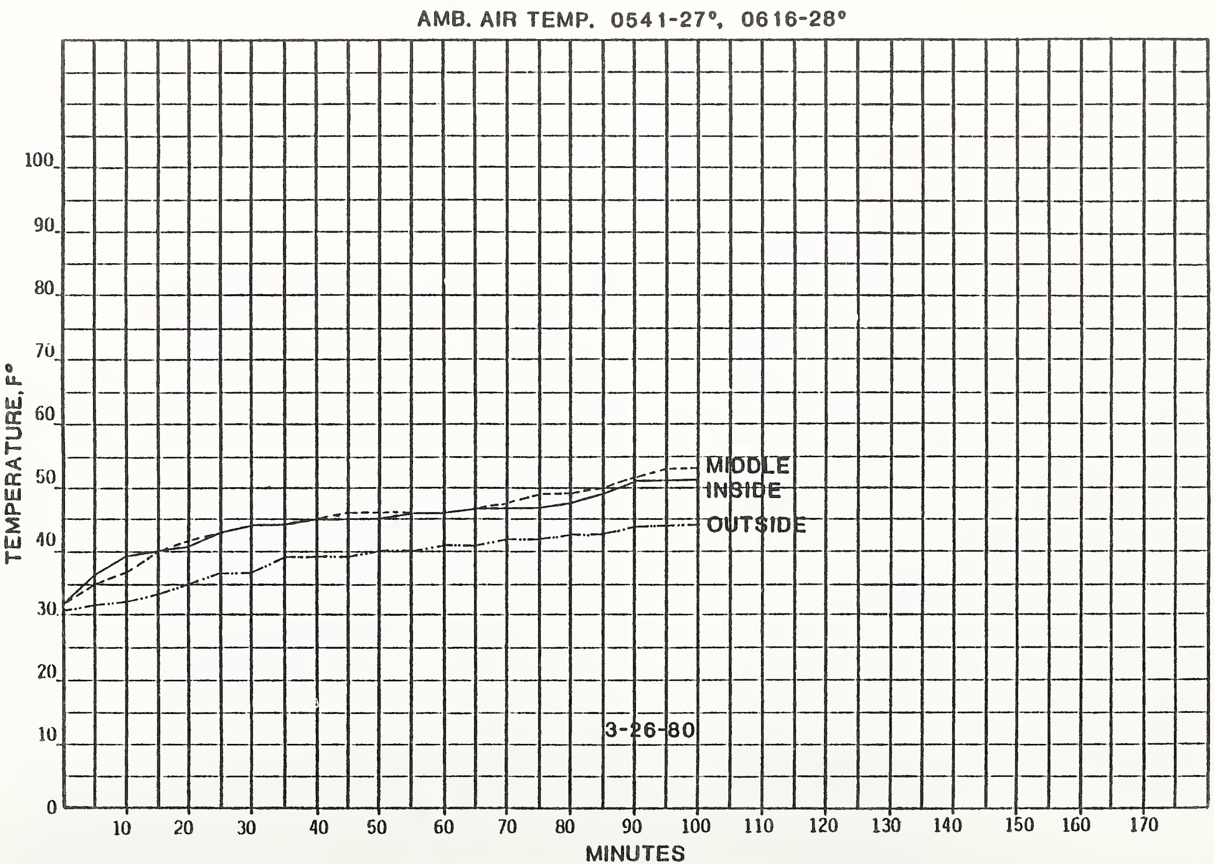


FIGURE 5-19. EMERGENCY BRAKE SURFACE TEMPERATURES AT 22 WATTS/FT

surface temperature vs. time. Brake surface temperature rose above freezing for most of the brake surface areas after approximately 30 minutes.

The power levels in the brake surface heaters were reduced to 25.5 watts/ft and then to 22 watts/ft. The results shown in the test run that was performed at power levels of 25.5 watts/ft indicate that the temperature rise is equivalent to that achieved using the 29 watts/ft level. At power levels of 22 watts/ft, the temperature rise was approximately 5^{o}F less than previous tests. Based on these test results, a 22 watt/ft heating power level is somewhat marginal to assure system operation and safety. Heating levels of approximately 25 watts/ft or 50 watts/ft/lane provide adequate assurance of deceleration braking coefficients in winter conditions.

5.3 GUIDEWAY SWITCHING

The OTIS-TTD system uses a passive guideway switch by switching an on-board vehicle-mounted mechanism. This mechanism locates wheels on one side of the vehicle or the other to follow a switching/retention rail. This switching and retention rail is shown in a guideway cross-section in Figure 5-20. The previous OTIS-TTD experience with winter operations of this passive guideway switch together with the test and demonstration conducted during the winterization program confirm that this guideway passive switching rail suffers no effects from the severe winter conditions. Even accumulations of ice and snow on this rail only cause a reduction of the ride quality in the lateral axis on board the vehicle. These types of precipitation accumulations would have no effect on the operation or actuation of this mechanism or the ability of the vehicle to route itself through a system network. The actual test conducted on the vehicle-mounted switching mechanism will be described in a later section on vehicle-related testing.

KEY:
1. POWER RAILS
2. SIGNAL RAILS
3. ANTENNA/TRANSMISSION LINE
4. GROUND RAIL
5. GUIDEWAY
6. BRAKE SURFACE
7. LIM SECONDARY
8. COLLECTOR ASSEMBLY
9. SWITCH RAIL
10. RETENTION WHEELS, SWITCHING ASSEMBLY
11. LATERAL GUIDANCE ASSEMBLY

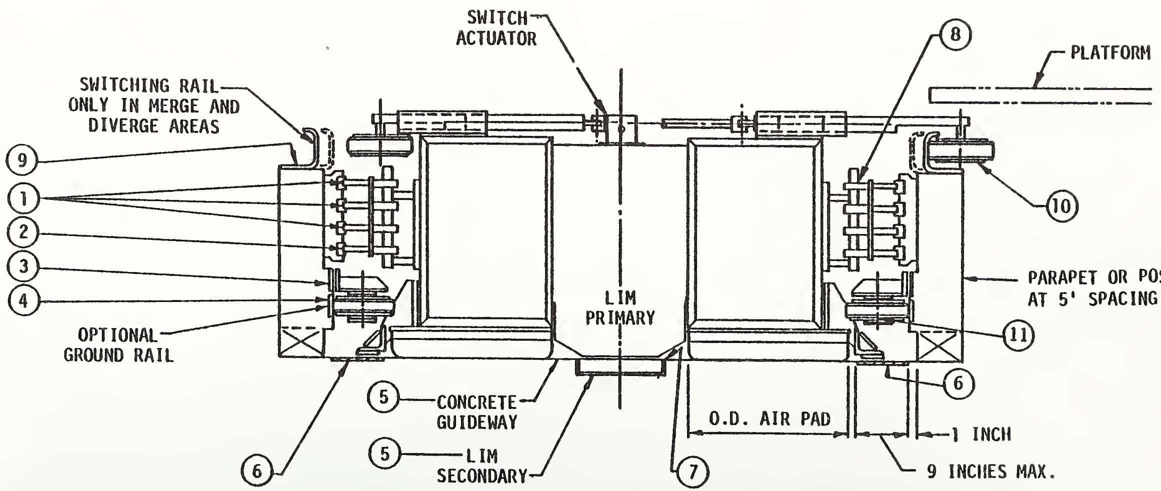


FIGURE 5-20. DUKE VEHICLE/GUIDEWAY INTERFACE

039-12-0151

5.4 OTHER GUIDEWAY SUBSYSTEMS

In addition to that already described, there is other hardware located on the guideway that might be subject to some limitations as imposed by severe winter weather conditions. Specifically, those areas tested for the effects of severe winter conditions include: continuous data communications and supplemental wayside sensors.

5.4.1 Continuous Data Communication Antenna

The OTIS-TTD Duke system utilizes the continuous helix wire inductive loop communications system which contains a guideway-mounted continuous flexible etched-circuit antenna throughout the system. This is interfaced with a vehicle-mounted receiving and transmitting loop with a separation of approximately 1 to 2 inches. This communication system was tested under winter conditions during the winterization test and demonstration program. A small segment of this communication line, approximately 60 feet in length, was installed, terminated and driven on the wayside by a fixed frequency carrier. This carrier was received on board the vehicle, detected and recorded to determine if there were any loss in communication signal during the operation of the test and demonstration program. The communication receivers on board the vehicle were not used in this demonstration because they have automatic gain loops on the front end providing 50 to 100 db of signal level control. During the entire operation of the test program, the approximate maximum variation in receive signal strength on board the vehicle was -3 db from nominal. Severe winter conditions will have no detrimental effect on the exposed portions of the communications system. Figure 5-21 shows a sketch of the tested communication link and Figure 5-22 shows a representative data trace with the received signal levels on board the vehicle.

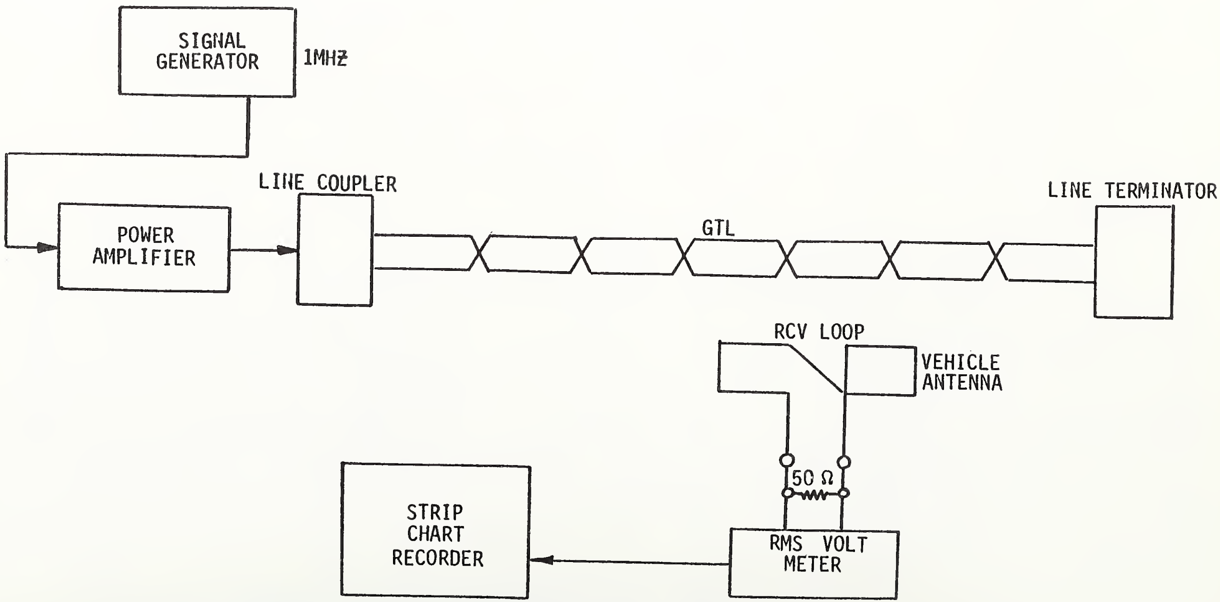


FIGURE 5-21. WAYSIDE/VEHICLE COMMUNICATIONS TEST SET-UP

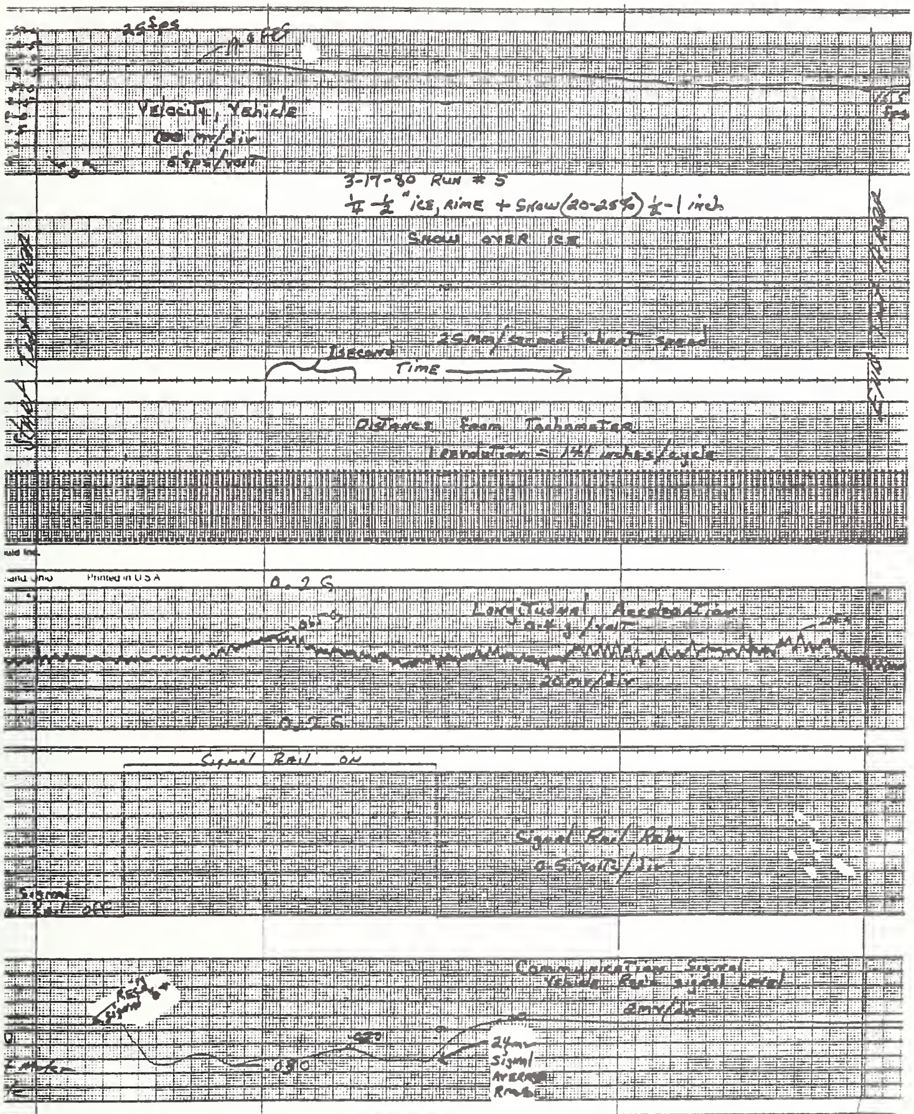


FIGURE 5-22. WAYSIDE/VEHICLE COMMUNICATIONS TEST DATA

5.4.2 Wayside Sensors

The OTIS-TTD Duke system, as tested at the Denver test track, utilizes wayside sensors to indicate stopping positions for the vehicle longitudinal controls. These sensors are located on the underside of the guidance rail and provide a tone signal generation which is received by the vehicle. All of these components are completely enclosed and sealed to prevent any degradation by moisture or high relative humidities. The operation of these wayside sensors was not influenced by the severe winter operating conditions as imposed during the test program. Safety assurance for automatic vehicle operations is provided through a fixed signal block wayside installation which is not subject to winterization effects beyond those experienced by the signal rail and vehicle-mounted shunt.

6. VEHICLE-RELATED TESTING

The OTIS-TTD test vehicles are based on the vehicle equipment configurations currently installed and in service at the Duke University Medical Center. As previously described in Section 4.1, a list of potential critical problem areas on board the OTIS-TTD vehicle were identified when that vehicle was subjected to severe winter conditions. It is the intent of the specific vehicle-related testing to expose these vehicle equipments, through the proper use of weather conditions and test/demonstration sequences, to the desired winter weather and evaluate their performance. The suitability of these various vehicle equipments to be winterized when warranted by various methods will be evaluated and incorporated within the vehicle. The vehicle-related winterization testing was performed in two specific sets of climatological conditions that were developed through the investigation of weather-climate histories in the regions of northern DPM employments.

The vehicle and related equipment were exposed to a cold test with temperatures below $0^{o}F$, and the effects of these low temperatures were observed or measured in the vehicle operation and performance. The effects of direct precipitations on the vehicle and associated hardware were also evaluated. Man-made snows were produced and deposited selectively on the vehicle and all exposed surfaces to represent the typical precipitations that a vehicle might come in contact with during a severe winter storm. These precipitations varied from dry to wet snowfalls with accumulations of up to 4 inches, and freezing rain/sleet with off-guideway accumulations of 1 to 2 inches with resulting buildups on the vehicle of 0.25 to 0.50 inches. Some vehicle equipment had specific provisions made for winterization to reduce or eliminate the effects imposed by the severe winter conditions. These were the vehicle chassis end shrouds and debris guards. These shrouds and guards were modified at several times during the test program to further enhance the ability of the Otis vehicle to operate in some of the more severe winter weather conditions. Vehicle operations in winter precipitations with below-freezing temperatures produced some effects on vehicle power and signal collection. These particular components were evaluated throughout the program and some specific recommendations as to changes were suggested.

The vehicle on-board guidance and route switching are accomplished through the actuation and extension of switch arms to one side of the vehicle or the other. The actuation of the Duke switch mechanism is not designed for dynamic route switching. The requirements for the Duke system are shuttle in nature and the vehicle route switching is accomplished manually while the vehicle is stationary or in a docking berth. The arms and switching wheels, which are the exposed portions of this particular vehicle equipment, are representative of a DPM installation. The vehicle-related testing that was performed using the Duke vehicle in 1978, and 1979, evaluated the effects of these vehicle-mounted guidance and switching arms by the weather conditions imposed upon them. During the 1979-80 winter season, an Otis test vehicle using the Duke chassis and a test body was used. This particular vehicle did not have the Duke switching arms or mechanisms as a part of its configuration.

Vehicle doors were evaluated using the Duke body during 1978 and 1979. The biparting vehicle side doors and the emergency-escape doors were evaluated under precipitation conditions and cold soak temperatures. The Otis test vehicle that was used in 1979-80 had a test-body configuration that did not have vehicle doors and actuators that were representative equipment. Therefore, the doors on this particular test body were not evaluated.

Vehicle propulsion and control were evaluated continuously during the test program to determine the requirements imposed upon them by the snow accumulations and winter conditions. The test area located at the OTIS-TTD test-track site contained a high reaction rail rather than the high conductivity reaction rail installed at Duke. The reaction rail installed at the Denver test-track site is suitable for use with many types of propulsion systems and does not produce the optimum thrust achievable using the Duke reaction rail and inverter propulsion control method. The reaction rail at the Denver test track produces approximately 70 percent of the thrust levels that are produced in the Duke system. Therefore, it is worthy of note that all of the vehicle testing that was performed at the Denver test site was accomplished with only 70 percent of the total vehicle thrust available. Any operation that could be performed in this test program under these conditions of reduced thrust levels certainly could be performed better and under even more severe winter weather conditions than was successfully demonstrated during the test program.

6.1 VEHICLE COLD SOAK TEST

The purpose of this test was to evaluate the OTIS-TTD Duke vehicle and vehicle subsystem performances at low temperatures (below $0^{o}F$ for 4 hours). This was to provide the requirements for low-temperature operation.

Extremely cold temperatures ($-10^{o}F$ to $-15^{o}F$) were forecast for the night of December 7, 1978. Duke Vehicle #3 was undergoing reliability tests for the night of December 7, 1978. Duke Vehicle #3 was undergoing reliability testing at the Otis test track and this vehicle was placed on the OTIS-TTD test-track siding and was exposed to temperatures below $0^{o}F$ for 12 hours. Weather information was documented as presented in Table 6-1. Upon arrival at the test track the following day, the ambient temperature was $-13^{o}F$, which was the highest temperature for the remainder of the test period. Refer to Table 6-2. Temperature A was located outside the vehicle at the center forward upper edge of the body in free air. Temperature B was located outside the vehicle on the center rear upper skin of the body. Temperature C was located in the inlet airstream of air suspension pad #10. Temperature D was located in the center of the rear air suspension/cooling blower bay. All sensors were calibrated and/or corrected to an ice bath reference. Battery power was applied to

TABLE 6-1. COLD SOAK TEST WEATHER DATA

Test: Wint-80340 (Low-Temp, No Precip.) - Climatic Data

Date: 12/8/78 Time: Start 04:30 Complete 08:30

Clock Time	Temp A West End °F	Temp B G.W. °F	Taylor Wind Scope Wind #3105		Remarks Buckley ANG Base Back Up 4 Miles		
			Speed mph	Direction	Relative Humidity	Temp	Barometer
0430	-13°F	-14	5	S	67%	-13°F	
0445	-13	-14.5	4	SSE			
0500	-14	-15	4	S			
0515	-15	-15	5.5	S			
0530	-15	15.5	8	SSE	57%	-12	24.43"
0545	-15.5	-16	5	S			
0600	-16	-17	6	S			
0615	-15.5	-16	7	SSE			
0630	-15	-16	6.5	S	59%	-11	24.435"
0645	-15.5	-17	6	SSE			
0700	-16	-16.5	6	S			
0715	-16	-15.5	6	S			
0730	-14.5	-13.5*	6	S	54%	-9	24.440"
0745	-14	-14	5	S			
0830		-10.5	5	SSE	55%	-8	24.445"

TABLE 6-2. COLD SOAK TEST VEHICLE TEMPERATURES

Time	Temp A	Temp B	Temp C	Temp D	Remarks
04:55	$-18^{\circ}F$	$-14^{\circ}F$	$+7^{\circ}F$	$-9^{\circ}F$	Battery Power On
05:10	$-18^{\circ}F$	$-13.5^{\circ}F$	$+7^{\circ}F$	$-9^{\circ}F$	
05:40	$-18^{\circ}F$	$-14.5^{\circ}F$	$+7^{\circ}F$	$-9^{\circ}F$	
05:50	$-18^{\circ}F$	$-14.5^{\circ}F$	$+6.5^{\circ}F$	$-9.5^{\circ}F$	Umbilical Power on
06:00	$-19^{\circ}F$	$-14.5^{\circ}F$	$+7^{\circ}F$	$-8^{\circ}F$	
06:30	$-19^{\circ}F$	$-11.5^{\circ}F$	$+3^{\circ}F$	$-6^{\circ}F$	
06:50	$-18.5^{\circ}F$	$-12^{\circ}F$	$+3^{\circ}F$	$-5^{\circ}F$	Air suspension on
07:00	$-18.5^{\circ}F$	$-13^{\circ}F$	$+24^{\circ}F$	$-3^{\circ}F$	
07:05	$-18^{\circ}F$	$-13.5^{\circ}F$	$+28.5^{\circ}F$	$0^{\circ}F$	
07:10	$-18^{\circ}F$	$-13^{\circ}F$	$+33^{\circ}F$	$0.5^{\circ}F$	
07:15	$-17^{\circ}F$	$-13^{\circ}F$	$+34^{\circ}F$	$0^{\circ}F$	Air suspension off
08:05	$-11.5^{\circ}F$	$-13^{\circ}F$	$+19^{\circ}F$	$-5.5^{\circ}F$	Prime Power on

the vehicle. The emergency ventilation blowers emitted a high-pitched sound for approximately 1 minute. Although insignificant to the performance of the vehicle, this could be eliminated by the use of a low-temperature lubricant.

The vehicle emergency doors or windows were unlocked by means of a latch release mechanism located outside of the vehicle body. Once a door latch has been released, the door swings to a full open position powered by a gas spring opener. Repeated door opening times were measured in this test. The vehicle passenger biparting doors located on the sides of the vehicle were operated manually from inside the vehicle. The door opening and closing times were measured through 6 cycles until fully opened or fully closed and locked. All door operations were completed without any difficulties. Slower door times were experienced after 9 door cycles on battery power. This would not be a valid deployed-system requirement.

The lateral guidance spring rate was measured by loading the left rear suspension bogie in increments of 0.25 inch of lateral deflection and measuring the applied load for each increment. This load configuration most nearly duplicates the static loads applied to the lateral suspension bogie by the guidance rail. A duplicate test was performed at 43°F later on in the program to establish the baseline values for the suspension bogie spring rates (See Figure 6-1).

AC auxiliary power was applied to the vehicle. The vertical suspension system flying height was reduced to about 30 percent of normal values for 1 to 2 minutes; it then gradually returned to normal. This reduced flying height seems to be a function of the stiffness of the air-pad membranes. The vehicle was levitated off the guideway with ample clearances and the vehicle drags were two to three times the normal levels. Due to the characteristics of the Otis LIM propulsion system, this vehicle drag increase is more than sufficiently offset by the increased thrust available due to the reduced propulsion motor air gap.

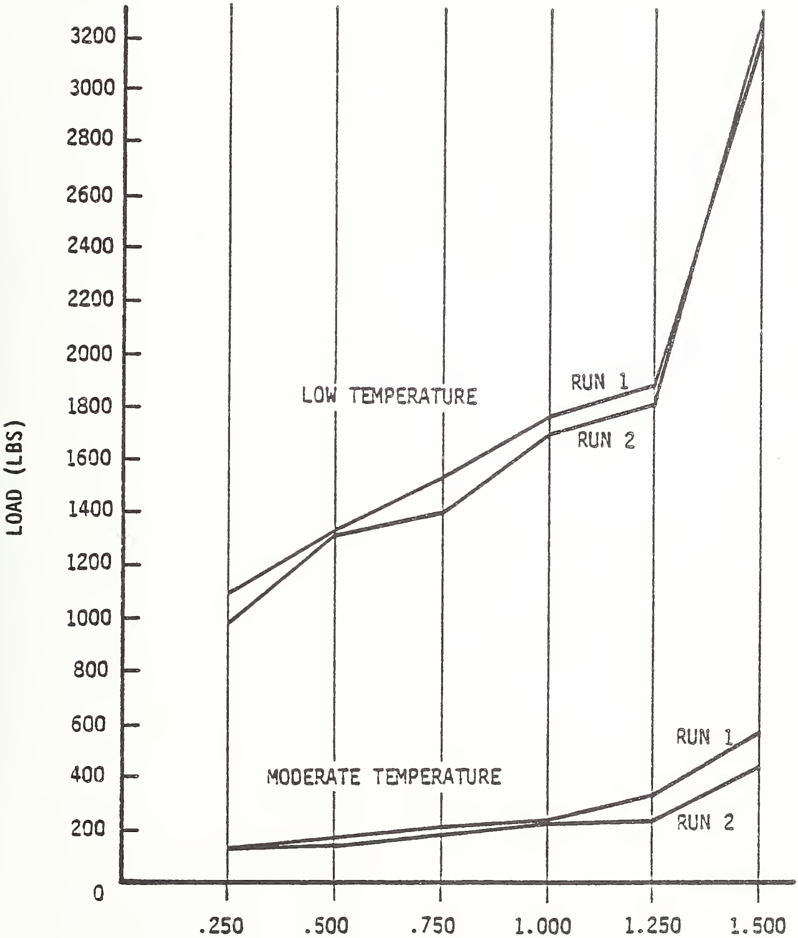


FIGURE 6-1. LATERAL SUSPENSION LOAD VS. DEFLECTION

With a temperature of -14^{O}F, the vehicle was put on the mainline loop and operated both manually and under automatic control. The on-board ink chart recorder that was to be used to record the various vehicle parameters of interest was frozen solid, so the remaining portions of the test had no dynamic vehicle data recorded, but subjective evaluations were made of the various areas of interest. The lateral and vertical ride quality was somewhat degraded due to the stiffness of the elastrometric components in the suspensions. This degradation of ride was in the form of higher frequency and amplitude of whole-body vibrations as sensed in the vehicle body. The ride, although degraded, was judged not to cause discomfort to passengers in short trips. After a period of approximately 1 hour of operation, the suspension components regained some of their elastic properties and the vehicle ride quality improved. It is projected that after some additional time these components would regain most of their normal characteristics. After vehicle operations, guideway power was shut down and vehicle friction and rolling drag (at 2 fps) were measured. The 20-lb increase in drag is close to the resolution of the measuring equipment and is of negligible consideration when compared to the 1500 lb of maximum thrust available from the linear induction motors.

The implications of low-temperature operation should be considered early in the design of a DPM vehicle and incorporated into the subsystem and system level specifications. In the design of the OTIS-TTD Duke vehicle, the North Carolina climatology dictated that vehicle design consider temperatures of 0^{O}F, and no consideration was given to the operation of this vehicle at temperatures below 0^{O}F. Further consideration should be given to material selections for the elastrometric springs to improve the ride quality performance limitations for system applications where anticipated temperatures frequently fall below -15^{O}F. This test sequence was to be repeated in the later portions of the program, but the equivalent low tmeperatures were never again observed over the remainder of the winterization test and demonstration program.

6.2 EFFECTS OF PRECIPITATIONS ON VEHICLE COMPONENTS

The effects of winter conditions, particularly those winter precipitations such as snow and freezing rain/sleet, on vehicle hardware and equipment were observed to determine the capability of the OTIS-TTD vehicle to operate reliably. The purpose of this test sequence was to verify the ability of the OTIS-TTD vehicle to withstand the effects of long-term exposures to adverse environmental conditions. The affected components of interest were specifically those exposed parts of the vehicle such as suspension, guidance, switching, power collection, vehicle doors, and the sealing provided by the vehicle chassis enclosure. The test vehicle was placed on the Otis test-track guideway in the winterization test section. With favorable conditions of temperature and wind, man-made precipitations would be accumulated on all of the exposed surfaces of the vehicle and its related equipment.

On February 21, 1979, the OTIS-TTD Duke vehicle was located within the winterization test section and positioned between two snow guns (Figure 6-2). The effect that the wind had on the production and placement of the man-made snow made it difficult to obtain a uniform deposit on the vehicle. This necessitated several changes in the location and position of the large snow gun. In the first position, designated position A, the gun was too close to the vehicle and the short air-exposure time of the water particles did not permit freezing and resulted in a very fast buildup of slush and frozen water on the right front corner of the vehicle. This slush in particular built up in front of the emergency-exit windows and fell down from the vehicle body surfaces onto the switch arm boot 6 to 8 inches deep.

The snow gun was moved to position B and this corrected the problem of the heavy slush deposits that were being formed on the vehicle. A later shift in the wind direction to the southwest made it necessary to relocate the large snow gun to a third position, identified as position C. The snow depths produced at various points around the vehicle varied from 1.25 to

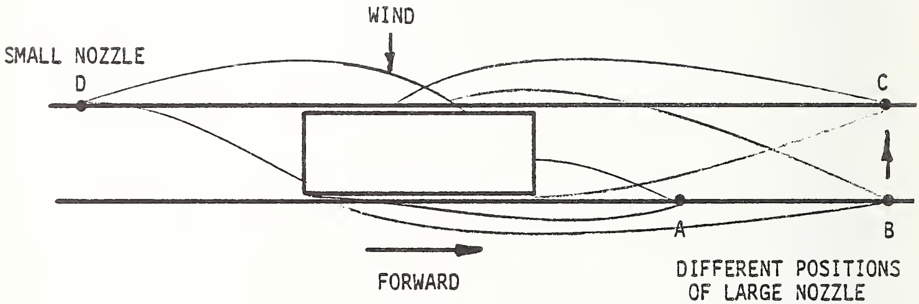


FIGURE 6-2. SNOW GUN POSITIONS DURING VEHICLE COMPONENT TESTS

2.25 inches in depth. The snow densitities were measured at three points and varied from 21 to 27 percent moisture content except for the heavy slush accumulations. The vehicle external components such as the power collector, lateral guidance assemblies, switch arm mechanism and vehicle tachometer were completely covered with a coating of snow, but did not show any measured or observed degradation.

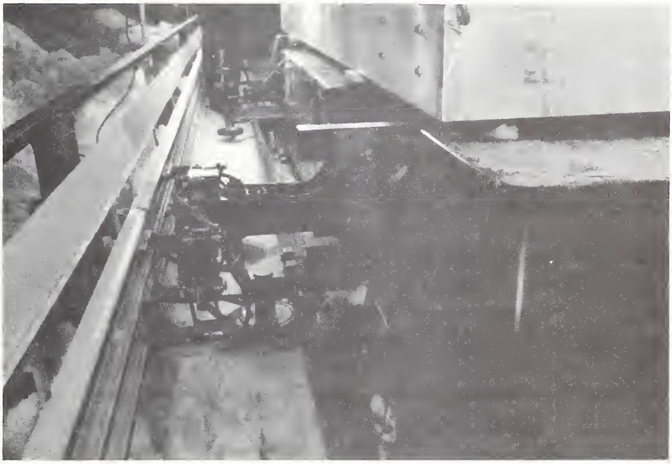
The vehicle was operated under prime power and no operational difficulty was noted or measured. The emergency-escape window which had been heavily impacted with the slush would not open with the power of its gas spring opening device, but was opened manually from inside the vehicle. The results of this test demonstrated the need for additional snowmaking capability such as: the provision of more air capacity to produce snow from two nozzles; the provision of more effective directional placement of the snows produced through the use of wind screens; and the provision of the ability ot relocate snow guns while in operation.

On the 12th of February, 1980, the Otis test vehicle, with shrouds, debris guards and winterization modifications in place, was located in the test section between two snow guns. The production of man-made snow was begun and continued for approximately 3 hours, depositing from 0.25 to 4 inches of snow accumulation with a water content of 15 to 30 percent on the vehicle and associated external hardware. After each snow accumulation was achieved, the vehicle tachometer drive wheel, power collector brush, signal brush and ground brush pre-loads were checked and found to be normal. These various arms and mechanisms, although covered with snow, moved freely and without obstruction. The vehicle auxiliary power was applied and air suspension system was operated with pad pressures, flying heights and manifold pressures measured. These measurements confirmed the normal operation of the vehicle air suspension system.

Guideway power was applied with the vehicle operating in automatic mode from a standing start and proceeding eastward through the test area and snow accumulations for a distance of several hundred feet. The vehicle was then programmed to operate in a westerly direction and traversed the winterization test area pushing snow accumulations that averaged 4 inches or more in depth from the guideway. The automatic operation of the vehicle after the impact of the snow accumulations was completely normal and no difficulties were encountered. After the initial pass through the test area, the guideway brake surface heating system was turned on, and approximately 1 hour later a successful emergency brake was demonstrated. Figures 6-3 and 6-4 show the vehicle and exposed elements both before and after the snow accumulations. Figure 6-5 shows the vehicle operating out of the snow impact area in the automatic mode. Figure 6-6 shows some vehicle-related hardware after automatic operations.

On the 29th of February, with the vehicle located in the winterization test section, 4 hours of freezing rain accumulations were deposited on the vehicle and the guideway. The guideway heating system was turned on when the applications of freezing rain began. The freezing rain was produced by supplying a very fine mist of water on the vehicle and guideway from spray nozzels. The application of freezing rain on and around the vehicle produced the equivalent accumulation of 1 to 2 inches. The actual buildup of frozen accumulations on the vehicle averaged 0.25 to 0.50 inches in thickness. Figure 6-7 shows the vehicle ice accumulations being formed. After the accumulation of ice, the pre-load spring rates were measured on the tachometer drive wheel, the power collection brushes, the signal collection and the ground brushes. All readings were normal with all mechanical members being free and unrestricted. The vehicle auxiliaries were powered and the air suspension system was operated with air pad pressures, flying heights, and manifold pressures all measuring normal, with no discrepancies or abnormalities noted. The guideway was powered and the vehicle was operated easterly in automatic mode out of the test area and then westerly through the test area. No abnormal conditions or operational difficulties were observed or recorded during this test. An emergency brake

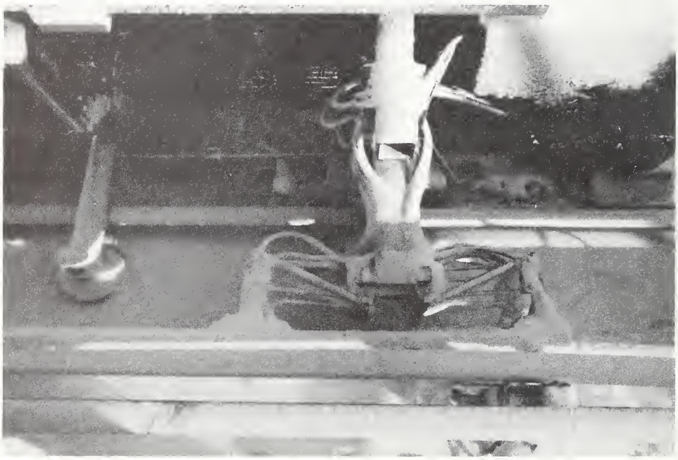
BEGINNING OF MAN-MADE SNOWFALL
ON VEHICLE, EARLY MORNING



POWER COLLECTORS AND TEST TRACK
ADAPTORS AS SNOW STARTS

FIGURE 6-3. VEHICLE ON GUIDEWAY EXPOSED TO SNOWFALL

LATERAL GUIDANCE BOGIE AFTER SNOWFALL



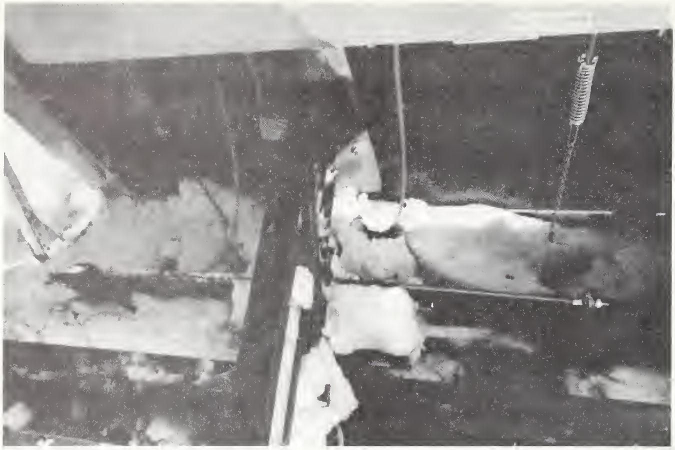
SNOW ACCUMULATIONS ON POWER COLLECTORS

FIGURE 6-4. SNOW ACCUMULATIONS ON VEHICLE

VEHICLE OPERATES OUT OF SNOW
AUTOMATICALLY, FIRST EAST

... THEN WEST FROM A STANDING START

FIGURE 6-5. AUTOMATIC VEHICLE OPERATIONS FROM SNOW BANK

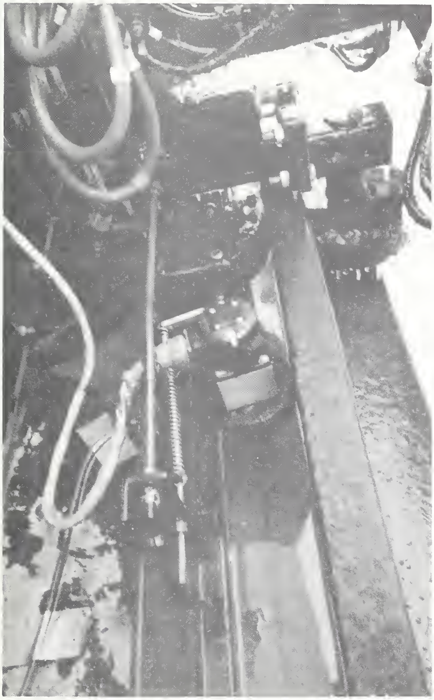


SNOWS STILL REMAINING AFTER
SYSTEM LEVEL OPERATIONS

POWER COLLECTOR AFTER SYSTEM LEVEL OPERATIONS

FIGURE 6-6. VEHICLE HARDWARE AFTER AUTOMATIC OPERATIONS

MANUALLY SPRAYING WATER TO ICE UP VEHICLE



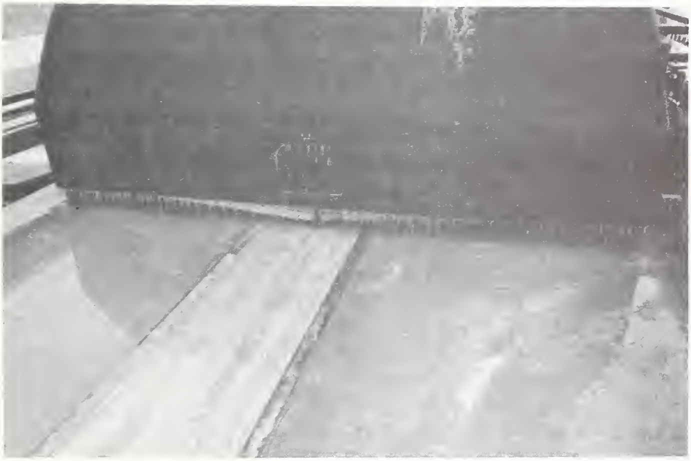
TEST TRACK ADAPTORS AND TACHOMETER ICING UP

FIGURE 6-7. ICING THE VEHICLE AND HARDWARE stop was performed in the test area with heated brake surfaces, producing normal emergency brake deceleration levels. The successful operation of the OTIS-TTD vehicle has been demonstrated after freezing rains with total accumulations of 1 to 2 inches. Figure 6-8 shows vehicle automatic operations after ice applications.

6.3 VEHICLE-MOUNTED WINTER SHROUDS AND DEBRIS GUARDS

The OTIS-TTD Duke vehicle uses a fiberglass-reinforced end shroud which is shown in Figure 4-8 to protect the end of the vehicle chassis and to allow an emergency-exit egress from the vehicle. The winterization test and demonstration program utilized these Duke fiberglass shrouds during the tests and demonstrations. This shroud was intially evaluated in the normal Duke configuration and then was modified several times during the program, improving the operational capability of the vehicle in snow accumulations.

The vehicle shroud assembly was first modified with additional reinforcement to react out the loads formed in pushing snows off the guideway. The underside of the Duke shroud clears the guideway surface by approximately 2 to 3 inches. During some snow removal demonstrations, snows would enter the bottom side of the shroud, and pack inside and around the vehicle chassis air intakes. The bottom side of this shroud was closed out and fastened to the vehicle chassis. These modifications allowed the vehicle equipped with the end shrouds to be used for plowing snow accumulations of up to 12.5 inches in depth off the guideway surface. It was demonstrated that a vehicle rear shroud was also required with the modifications that have been installed on the front shroud to maintain the operating capabilities of the vehicle through all types of severe winter demonstrations. Figures 6-9 and 6-10 shows the OTIS-TTD test vehicle pushing snow accumulations with the end shroud. The shroud with its winterization modification proved successful in removing many types of snows from the guideway. It is recommended that vehicle shrouds for



VEHICLE STARTS TO OPERATE AUTOMATICALLY
OUT OF ICE STORM

VEHICLE UNDERWAY WESTBOUND AFTER ICE STORM

FIGURE 6-8. VEHICLE OPERATIONS IN ICE

SYSTEM-LEVEL TEST ON 3-17-80

VEHICLE PUSHING SNOW ASIDE AND
POWER COLLECTOR RUNNING IN SNOW

FIGURE 6-9. AUTOMATIC OPERATIONS IN MAN-MADE SNOWFALL

VEHICLE CIRCULATING THROUGH MAN-MADE SNOWFALL

GUIDEWAY CONDITION AFTER CIRCULATION

FIGURE 6-10. AUTOMATIC OPERATIONS SHOWING SNOW REMOVAL for DPM winter installation and deployment be designed with a built-in snow prow. This prow would improve the removal of snow accumulations from the guideway surface. This snow prow, as envisioned, is a simple contoured V-shape modeled into the vehicle end shroud with no visual or aesthetic impact upon a normally-operating vehicle.

The debris guard shown in Figure 4-8, as equipped on the Duke vehicle, is a V-shaped wiper installed ahead of the leading edge of the chassis and air suspensions pads. It is fastened to the vehicle chassis frame and bumpers and is equipped with a flexible rubber strip which almost contacts the guideway flying surface while the vehicle is levitated. The original Duke debris guards were modified during the winterization program to materially extend the operation of the Otis test vehicle in the severe winter precipitations. The primary function of the debris guard in the winterization installation is to clean the flying surface of snow residues after the plowing performed by the end shroud or snowplow to prevent those snows from passing underneath the vehicle. It was found that the optimum performance of the vehicle related directly to how these debris guards were installed and how effective they were in cleaning the guideway surface. The Duke debris guards were modified to improve their effectiveness, which maximized the performance of the vehicle during severe winter conditions. After these modifications, the debris guards operated successfully throughout the program. Winterized DPM vehicles must undergo inspections of their attendant winterization modifications at strategic intervals to assure reliable system operations during the advent of severe winter weather conditions.

6.4 VEHICLE POWER AND SIGNAL COLLECTION

The OTIS-TTD vehicle uses a Howell power collection and distribution system for the main vehicle power distribution and for fixed block signal rail. These power collection assemblies provide three axes of freedom and contact the rail surfaces with torsional pre-loads provided by fixed wire springs of 8 to 10 lbs per brush. Each rail is contacted by a redundant pair of brushes that are independently articulated and pre-loaded to the rails. The Howell power rail is an aluminum extrusion with an inverted stainless steel contact surface and provisions for installing heater wires in the front edges of the rail. These rails (230 feet of the test section) were heated during the winterization test and demonstration program. On many occasions during the winter season, natural winter precipitations with below-freezing temperatures made vehicle operations impossible on the remainder of the guideway not equipped with power rail heaters. The test section equipped with power rail heaters provided reliable operation throughout the most severe winter conditions in the test program. The only winterization provision taken for the on-board power and signal collection assemblies was to lubricate the pivots with a silicon-based low-temperature lubricant. During automatic system-level tests, the vehicle was successfully circulated through the test section and the winter precipitations 20 to 30 minutes after the application of heating power to the power distribution and signal rails. This interval was eventually reduced to less than 15 minutes and the power distribution system functioned without any adverse effects, but the signal collection system had a signal dropout which may affect automatic operations.

Power collectors were affected several times while using the snowplow to clear large accumulations of snow from the guideway. The power collection assembly was located on the right front corner of the test vehicle under the wing of the snowplow, which subjected it to the spillage of snows from snowplow operations. When using a vehicle equipped with a snowplow for clearing snow accumulations from the guideway, the plow should be installed at the opposite end of the vehicle from the power collection assembly. It is advisable that the power collector assembly have shrouds enclosing the top side and the leading edge to prevent snow accumulations from fouling the power collector arms and contacts. This shroud would improve the operating capability of the vehicle during extremely heavy snowplowing operations. Enclosed face insulative covers for the power rails would also improve operations in heavy snows. Power collection or signal collection dropouts were only experienced once during the program, when the power rail heaters were allowed to warm up for approximately 45 minutes. This power dropout occurred while plowing snow with the test vehicle in manual mode. The integrity of the power and signal collection systems seems to be adequately assured by the use of the guideway power rail and signal rail heating techniques employed. Figures 4-3 and 4-10 illustrate the power collection and signal collection mechanisms as installed on the Otis test vehicle.

6.5 VEHICLE GUIDANCE SWITCHING

The OTIS-TTD system utilizes an on-board vehicle-actuated guidance-switch mechanism. This mechanism extends arms containing switch wheels on one side or the other of the vehicle. This arm slides in a bearing moving approximately 1.5 feet. The actuation of this switch mechanism on the Duke vehicle is slow because all switching operations are performed while the vehicle is stopped. The switch arm, its actuator, and the various electrical and mechanical interlocks are located on the top of the vehicle chassis under the body. For winterization testing this particular area was sealed using a high-density foam to prevent winter precipitations from entering and affecting the operation of the switch mechanisms. The movable arms themselves were covered with flexible boots to prevent snow and ice accumulations on the arms where they entered the sliding bearings. In vehicle component tests, it was discovered that heavy accumulations of wet snows could drop onto the flexible boot and freeze, creating high switch arm actuation loads. This particular problem could be eliminated by the use of a heated flexible boot. The test-track-guideway retention/switching rail is not compatible with the Duke switch arm, thus no dynamic tests of the vehicle switching capability were performed. The vehicle used in the second season of the winterization program, the Otis test vehicle, had no on-board switching mechanism. This vehicle has a fixed retention for operations at the Denver test track. The guidance/retention tires used on the Otis test vehicle were the same ones used on the Duke switch arm, and were operated throughout the program showing no effects from the severe winter conditions.

6.6 VEHICLE DOORS

The OTIS-TTD Duke vehicle is equipped with biparting passenger doors on either side of the vehicle. These doors are operated by mechanisms located in the ceiling of the vehicle body. The doorway openings on the Duke vehicle are extra wide, allowing large pieces of cargo to be easily moved on and off the vehicle. The doors were evaluated under the low-temperature cold soak test and the effects of these temperatures noted. When the Duke vehicle was subjected to precipitations of heavy wet snows, the door mechanism guides and operators were subjectively evaluated, and no discernible effects were noticed on door operation. Vehicle door operation in a system deployment using the Otis vehicle and related station hardware would be adequately sheltered from the effects of a majority of the severe winter conditions in a station docking berth. The vehicle door seals designed for use in Durham, North Carolina, would probably be redesigned for a DPM installation with a severe winter climate.

6.7 VEHICLE PROPULSION AND CONTROL

Both Otis vehicles used in the winterization test program, the Duke production vehicle and the Otis test vehicle, were controlled by a pulse width modulated variable-voltage variable-frequency propulsion inverter. The 3-phase 500-volt AC distribution was converted to a 650-volt DC bus, which was commutated into the linear motor windings under the supervision of a microprocessor-based inverter logic unit. This particular propulsion system has the capability of producing acceleration levels of

0.12 g on "high conductivity" or Duke reaction rail. While operating at the Denver test track with the "high resistivity" reaction rail it can produce acceleration levels of 0.085 g.

Vehicle longitudinal control was provided by an on-board microprocessor-based velocity control unit which commanded the vehicle automatically to selected velocities. The recording of propulsion power levels on board the vehicle provided a relative measure of the amount of additional power required while circulating through the snow and ice conditions. Figures 6-11 and 6-12 represent some of these typical propulsion power recordings which were taken while the automatically-controlled velocity was maintained through the ice and snow accumulations in the winterization test section. These propulsion power levels represented the thrust required to maintain the vehicle velocity through the test section, and typically varied from values equivalent to the normal cruise thrust up through the maximum capability of the propulsion system. The recorded propulsion power levels were a function of the amount and type of snow that was cleared from the guideway surface. No effects were noted in the propulsion or propulsion control systems on board the vehicle due to the effects of the winter conditions.

During freezing rain and sleet conditions, ice accumulations built up on the guideway surface to a depth of 0.5 to 0.75 inches. When this occurred, typical LIM power requirements were higher than those in normal operations due to a larger motor air gap, but the resulting thrusts produced by the motor were roughly the same. More input power is used to yield the same thrusts. The maximum power requirements for the propulsion system occur when operating at the time ice accumulations start to melt and break away from the surface. When this occurs, patches of discontinuour ice result and this rough surface reduces the efficiency of the vertical air suspension, creating higher vehicle drags. In all cases when these conditions occurred in 1980, the vehicle negotiated them successfully, with some degradation in velocity but no vehicle stoppage.

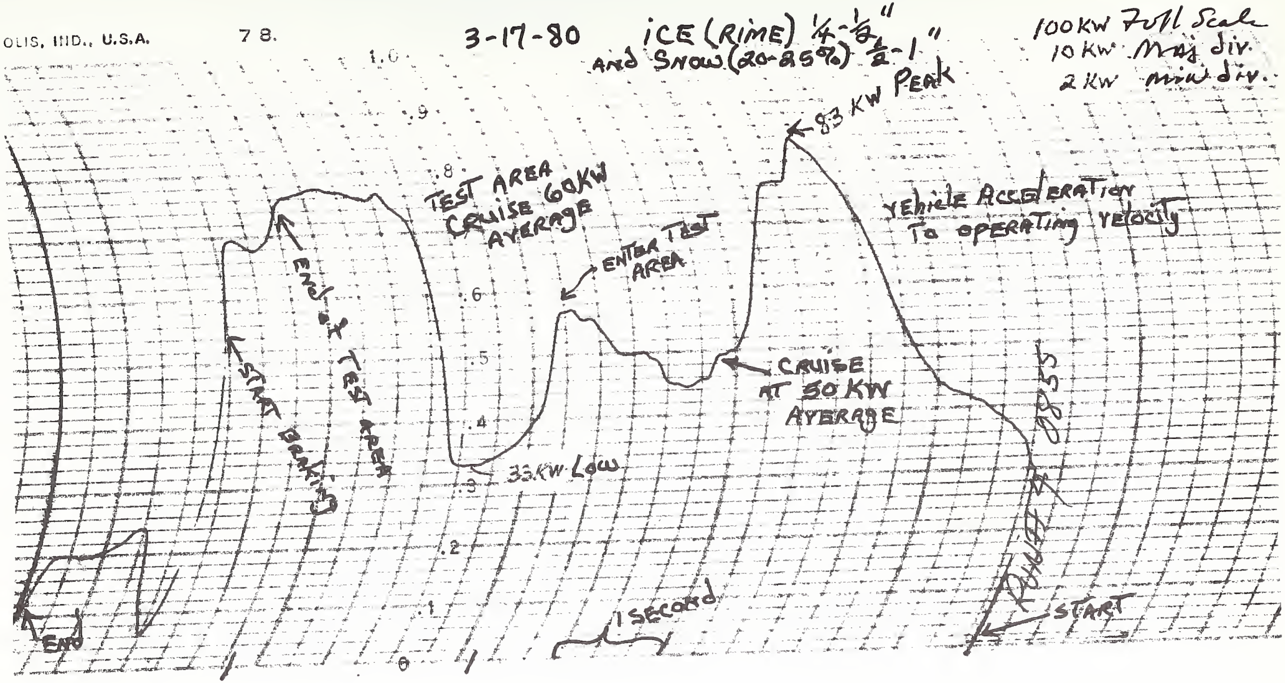


FIGURE 6-11. VEHICLE PROPULSION POWER RECORDINGS IN WATTS

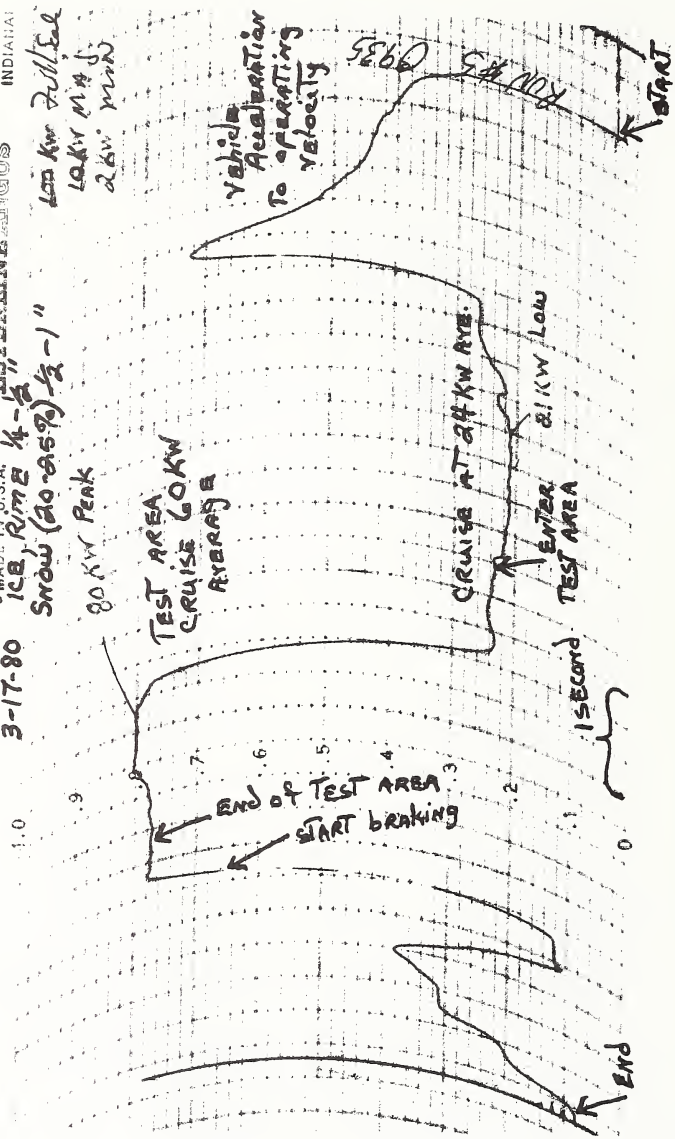


FIGURE 6-12. VEHICLE PROPULSION POWER RECORDINGS IN WATTS

The velocity control unit maintains the vehicle speed within 5 percent of a predetermined value. When the speed is reduced, the velocity control unit requests additional motor thrust to correct for these conditions. The velocity control unit gains were set such that the maximum thrust of the vehicle would be requested when the vehicle speed fell 10 to 15 percent below its predetermined operating value.

7. POWER DISTRIBUTION AND SIGNAL DISTRIBUTION SYSTEM TESTS

At the OTIS-TTD Denver test track, the vehicle power is provided by a 3-phase 500-volt AC distribution system. The power rails used are Howell 1000-amp aluminum rails that have an inverted contact area with a stainless steel contact face. These rails were heated over a 250-foot length. Also in the area where these rails were heated, a standard molded polyvinyl chloride insulated cover was evaluated for its ability to retain the heat produced in the rail. The power rails are supported by stanchion posts at 7.5-foot intervals, suspending them approxiamtely 6 inches outboard of the lateral guidance/retention rail.

The power distribution tests were conducted in conjunction with the system-level vehicle circulation testing on over 20 different days, primarily during 1980. The power distribution system was exposed to test conditions in temperatures from -15°F to 45°F, with different snow types having water content of less than 15 percent in excess of 45 percent. The snows, most of which were man-made, were produced at accumulation rates in excess of 2 inches per hour to accumulated depths of up to 25 inches. Glaze and rime ice were produced on 7 different test days, exposing the power distribution system to all of the various icing conditions. It became clearly evident through test operations that under most icing and frost conditions, the test vehicle was inoperative without power rail heating. With snow accumulations, vehicle operations were possible on unheated rails under conditions of extremely cold temperature and light snowfalls occurring with light winds. Snowfalls that occurred with wind speeds above 10 mph and ambient temperatures near freezing created frozen accumulations in the unheated power rails, making them unsuitable for operations. It should be pointed out that the power rails at the Otis test track are completely exposed to the winter weather conditions.

To assure complete reliability in the power distribution system, a certain amount of heating must be provided for the power rails. The level of heating was evaluated and approximately 8 8 to 10 watts/ft per rail would allow reliable system operations under all the severe winter weather conditions. The heating of power rails at these levels could be initiated at the first sign of impending precipitations or frosts. The measured warm-up time of 15 to 20 minutes would allow system operations to be continued without interruption and only slight delay. This operating scenario may be advisable because of the unpredictability of the weather and hence the unreliability of weather forecasting. If weather precipitations were anticipated 15 to 20 minutes in advance of their occurrence, system operations could be continued without any delays. Figures 5-9 and 5-14 illustrate the power rails installed at the Otis test track, the power rail heating wire installation, the protective insulative covers, and the temperature measurement sensors that were used to evaluate the heat-rise profiles.

Some different types of rail shrouds and covers were experimentally or analytically evaluated as to their potential effectiveness in materially extending the operational capability of unheated power rails. The feasibility of this approach was not good because reliable operations could not be assured under the wide variety of winter conditions. One particular concept that looks interesting is insulated covers for each individual rail with a closed face. This complete enclosure would allow further optimization of the power rail heating levels, and would assist in preventing a collector brush from coming completely off a power rail.

Where power rails were heated, the system-level tests never experienced a power-distribution-related shutdown. Also, no measured momentary power dropouts occurred during these system-level tests.

The physical location of the power distribution rails in the present test-track configuration, which is 3 verticallystacked rails with the highest rail approximately 25 inches above the guideway surface and the contact surfaces in a vertical plane, may be improved. A location which would allow better snow removal around these power rails and provide an enclosed area with the orientation of the contact surfaces down in a horizontal plane would be a better winterized power distribution approach. These changes would materially improve and extend the winter operational capabilities of the OTIS-TTD system.

The OTIS-TTD test vehicle that operated at the Denver test site during the winterization test and demonstration program was controlled automatically from on board the vehicle. The test-track guideway does not have a Duke signal block safety system installation. A length of Duke guidance rail, communications antenna, and signal rail were installed in the winterization test section. The signal rail was installed and heated using the same techniques as the power distribution rail. The heating power levels selected for the signal rail were higher than those used for the power distribution rails. These heating power levels were later reduced to achieve an optimal heating level because the initial equilibrium temperatures were higher than necessary.

The vehicle interface for the signal rail at the test track was a shunt containing the vital relay. The vital relay contacts were monitored and the relay energized via the commanded signal on the signal rail. The integrity of the signal rail contact was verified by monitoring the contact closure and continuously recording this information on board the vehicle. Figures 7-1 and 7-2 show a sketch of the signal rail test installation and a sample of the typical recorded data. OTIS-TTD has the capability of handling block and signal information on the wayside communication system for a winter climate deployment. This would provide some natural advantages in that no mechanical moving parts are required and the communication antennas are unaffected by the winter climatic conditions.

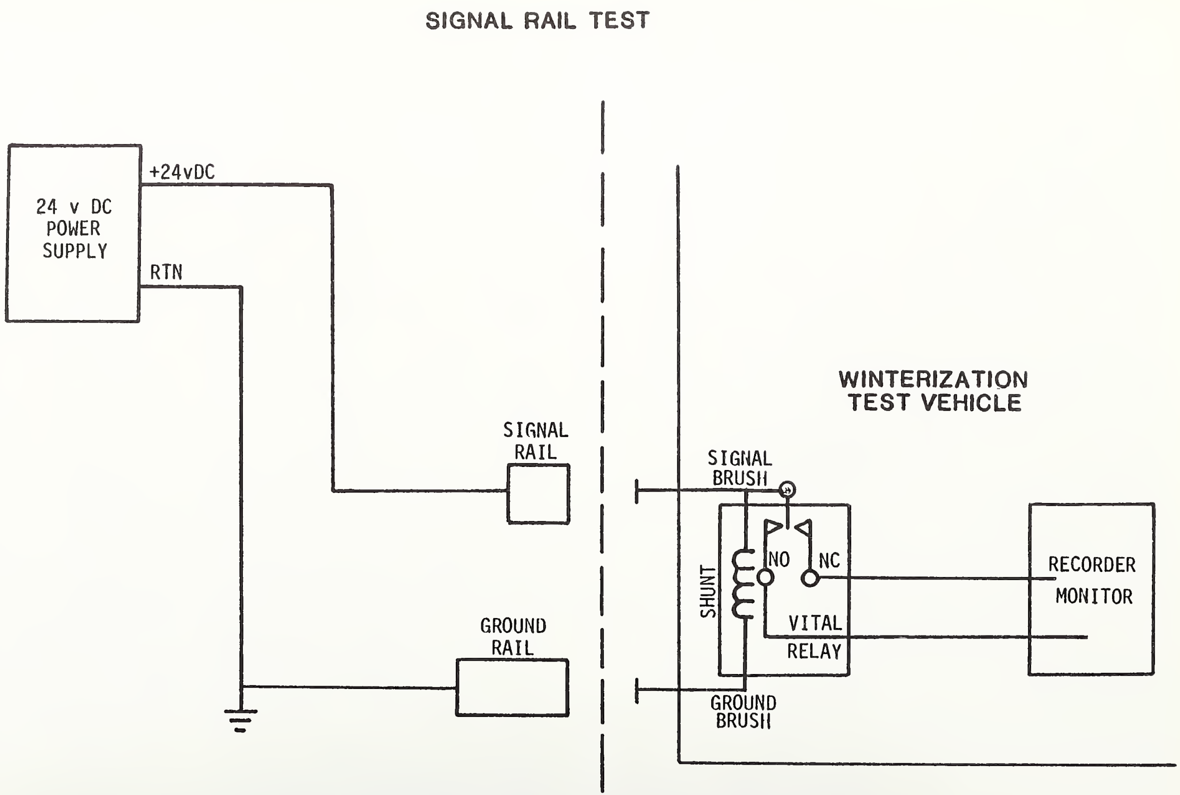


FIGURE 7-1. SIGNAL RAIL TEST SET-UP

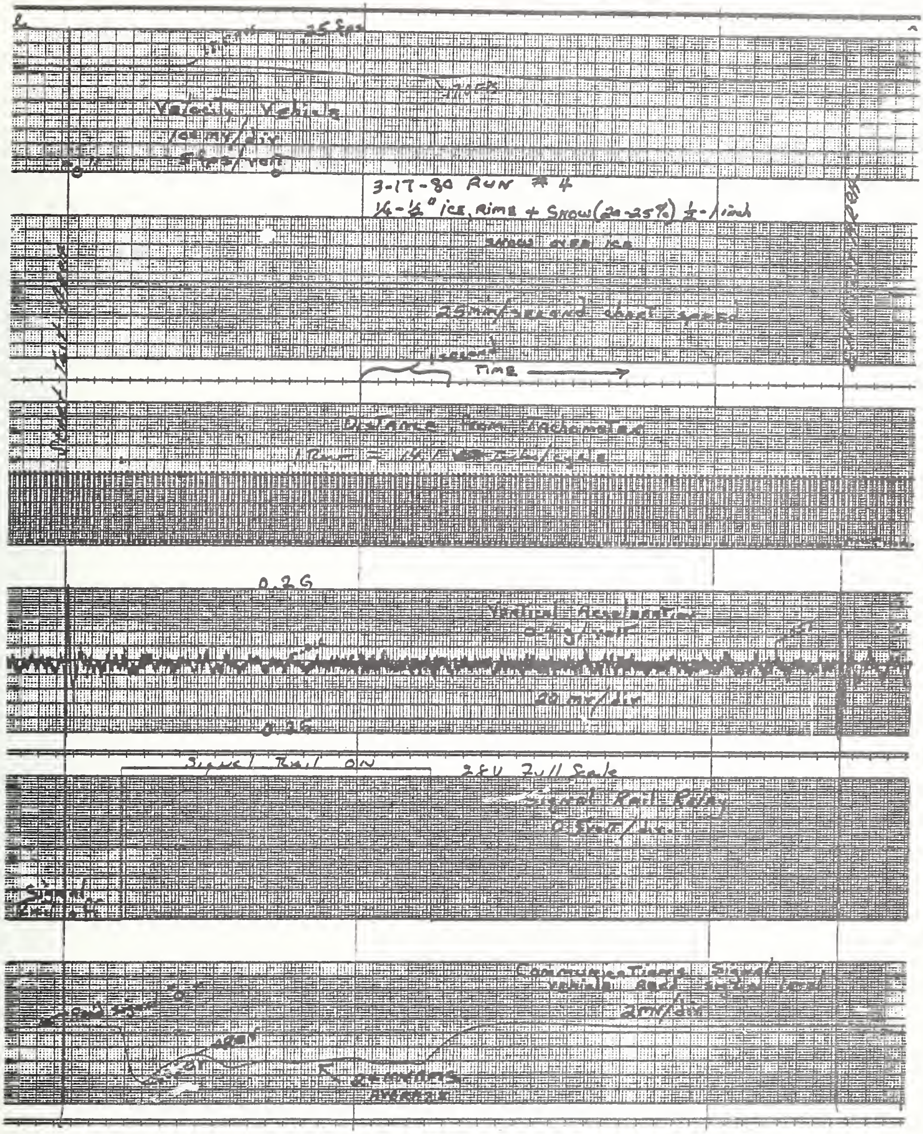


FIGURE 7-2. SIGNAL RAIL TEST DATA

8. OTHER SUBSYSTEM TESTING

The OTIS-TTD winterization demonstration program was performed using the Duke vehicle with related hardware and operated at the Denver test track. The Denver test track configuration was originally built for the Transpo '72 vehicle and was modified to enable Duke vehicle operations. This vehicle/guideway interface had limited capability and was used for test and checkout purposes. The vehicle and guideway system allowed the evaluation during the program of all the critical vehicle and guideway hardware. Some of the specific hardware items that were evaluated during severe winter conditions were not completely typical of those in deployed systems.

The lateral guidance assemblies on the Duke vehicle and the Otis test vehicle operated without difficulty throughout the program in all types of precipitations, temperatures, and other severe operating conditions. Demonstrations verified that this hardware as configured was suitable for winter climate deployments. The actual quantitive lateral guidance performance is not typical of a system deployment because of the fixed retention arms used and the Denver test site guidance and retention rails. The laterial guidance bogie sliding bearing was adequately protected by the use of the winterization boot modification. No component of the vehicle was heated at any point during the performance of the program. This was an effort to show that winterization vehicle performance would be adequate without performing any heating on board the vehicle, unless proven by tests and demonstration to be absolutely required for the successful performance of the test scenarios.

Snow fencing was considered to be valuable in limiting the effects of drifted snows on at-grade guideways. Investigation of this item was not included as a part of the winterization test and demonstration project, as extensive information on snow fencing and its suitability for various installations is available from highway programs.

A specific area of interest that was outside the scope of the OTIS-TTD winterization test and demonstration program was the effects presented by the snows that were removed from the guideway and deposited outside the guideway areas. The guideways designed for at-grade installations need room for depositing snows removed from the guideway running surface areas. These snows then need to be melted or removed during an extremely long winter season to allow the continued and additional removal of guideway snow accumulations. Consideration must be given in the DPM system to allow for providing these specific services. The effects of snow removal on surrounding property must also be evaluated and the effects understood, particularly in the case of elevated guideways.

An evaluation of DPM system stations was not a part of the OTIS-TTD winterization program, but some general recommendations can be made based on winter climatic experiences and results achieved from guideway precipitation accumulations. A certain amount of heating, shrouding and enclosing of critical station-related equipment should be considered. These winter modifications would be easier to install and more cost effective than guideway winterization modifications in that they would be confined to a small local area where ready provisions for some of these modifications would already be available. The effects of precipitations and their accumulations, of winds, and of cold temperatures would be somewhat naturally reduced in station areas because of their proximity to building structures and other types of construction. The wayside controls such as: signal and block control, track and interlock, mode and dispatch, central control operations, and communications were not evaluated because these equipments are installed in station buildings or other enclosed and climatically controlled areas where the effects of winter conditions are not felt. These wayside controls are only susceptible to winter conditions to the extent of any remote vehicle- and guideway-mounted hardware. This hardware was evaluated during the winterization program.

A requirement from the experience gained in the winterization program would be to include a reliable weather forecasting capability as part of a DPM system deployment operational policy. This weather forecasting, if provided from more than one source, could be considered reliable and independent of potential man/machine error influences. The weather forecasting information could then be utilized to anticipate specific types of winter conditions and preventative or corrective actions could be taken early enough to prevent loss of system availability that might be imposed by these conditions. For a winter climate DPM installation, an experience base with weather forecasting information should be gathered approximately 2 years prior to system-level operations to insure the reliability of the information and to equate the system user with the optimal use of the information to assist the system performance. It is conceivable that once this forecasted weather information is obtained, it could automatically be utilized to control some of the winterization corrective measures that would need to be taken to assure reliable system operations.

9. SYSTEM-LEVEL TESTS

The OTIS-TTD winterization operational philosophies considered the system-level performance valuations as being the most significant and most important in demonstrating successful severe winter weather operations. The Otis test vehicle was operated on more than 20 different days in a wide range of severe winter weather conditions. The vehicle was shuttled through the test area in the on-board automatic mode utilizing the VCU longitudinal control system to operate the vehicle at a preselected velocity and to provide thrust, acceleration, and jerk control through a range of speeds. The test conditions that the system was subjected to during these circulation test runs ranged from snow accumulations with a moisture content of less than 15 percent, man-made snows with a moisture content of 15 to 30 percent, man-made and natural snows with a moisture content greater than 30 percent, glaze icing conditions simulating freezing rains, and rime icing conditions simulating sleet and water refreeze conditions, with various wind and temperature conditions. In the winterization program it was shown that a circulating OTIS-TTD vehicle could adequately remove up to 1 inch of snow accumulation regardless of: the water content, the ambient temperature, and the guideway conditions. This led to a criterion, based on the requirements imposed for the winterization demonstration that vehicles be circulated through the snowfalls at intervals of 30 minutes. In many different cases during the winterization program snow accumulations of much more than 1 inch were satisfactorily removed from the guideway by normal system-level vehicle operations.

The test scenario for demonstrating system-level operations of vehicles during winter precipitations was based on the modifications to the winterization test section and the capability of the snowmaking equipment to produce suitable winter conditions. This resulted in a 250-foot length of guideway which was described as the winterization test section where the vehicle circulation took place and where documentation either by on-board recorders or photographic and video records verified the performance of the system-level tests. The actual vehicle circulation operations and attendent snowmaking were generally conducted in 8-hour periods starting with the coldest portion of the day, which usually occurred between 3 and 5 o'clock in the morning, with tests continuing through the morning hours to take advantage of the improved lighting conditions. Supplemental lighting was provided in the winterization test area for photographic and video tape documentation prior to sunrise. As the system-level tests progressed, the vehicle-mounted shrouds and debris guards were modified to improve the capability of the vehicle operation. It was not possible during the winterization program to catch very many natural conditions that satisfied the requirements of the test matrix in the system-level tests. Therefore, most of the system-level test operations were conducted with man-made precipitations that could be produced and controlled at will, providing an optimization of the test crew and test track usage. In three cases (under different sets of conditions), tests were conducted over three successive test days, representing significant on-guideway accumulation of snows and simulated snow storm events depositing precipitations at the maximum rate specified for more than 20 consecutive hours. These test series, which were performed successfully, were well in excess of the requirements specified in the desired climatological extremes.

9.1 BASELINE TESTS

The system baseline tests were conducted utilizing the same scenarios performed during the system-level tests with attendant severe weather conditions. These baseline tests were performed several times at moderate temperatures (those above 40^{o}F) and without precipitations. The vehicle was operated using the on-board automatic controls at various speeds through the winterization test section while monitoring and recording the various vehicle parameters of interest. Additionally, photographic and video tape documentation was produced during these particular baseline test runs. All of this information was used to produce a well-defined normal operations envelope, which then could be compared to the operational characteristics, data points and evaluations experienced during the severe winter weather conditions. The vehicle, in addition to the system-level baseline tests, performed a series of emergency brake stops in the test area to determine the normal deceleration levels and stopping distances, for comparison to the emergency brake tests conducted during the winter precipitation conditions. More extensive tests of baseline conditions were performed on the vehicle subsystems as a part of the cold soak temperature test. These evaluations included door cycle times, emergency exit operations, lateral guidance assembly spring rates, vehicle flying heights, pad pressures and manifold pressures, vehicle frictional drags, power collector brush pre-load tensions, ground brush pre-load tensions, tachometer drive wheel pre-loads, and other subjective evaluations of specific interest. The data recorded and information presented are available in Section 6.1.

9.2 SYSTEM-LEVEL TESTS IN SNOW EVENTS WITH A WATER CONTENT OF LESS THAN 15 PERCENT

On February 7, 1980, a system-level test was started under glaze ice conditions. Within a few minutes after the initial ice application, a natural snowfall began. The first automatic ciculation run of the vehicle was conducted at 6:00 in the morning and five automatic vehicle circulation runs were made over the glaze ice at 1-hour intervals, with each run removing 0.5 to 1 inch of snow and slush. After the third run some glaze ice had come loose, producing a discontinuous ice surface. After the fifth run the guideway surface as 90 percent clean and wet, with two more back-to-back runs leaving a clean and wet guideway. The snow storm continued with winds of 13 mph and a steady temperature of 26^{o}F. The vehicle was parked on the guideway overnight. No problems of any kind were encountered during circulation of the vehicle. The off-guideway accumulation of snow at this particular time was approximately 4 inches.

When operations commenced again the next norming, approximately 3 to 5 inches of additional snow had fallen, bringing the total accumulation of the storm to 8 to 9 inches. The moisture content of this particular snowfall event was 11 to 12.5 percent. The guideway conditions included 12 inches of drifted snow accumulations over 25 percent of the guideway surface. The vehicle was circulated in the automatic mode through the snow accumulations on the guideway. During operations, accumulations actually rose above the top of the vehicle end shroud. After removing all but 30 to 40 feet of the snow in the test area, the vehicle was moved back for another run into the accumulated bank of snow that was left on the guideway. This was accomplished and the remainder of the test area was cleared. An irregular layer of rough ice up to 5/8 of an inch thick remained after the clearing operation. Snow was packed in and around these ice accumulations on the guideway, filling in low spots and voids with compacted snows, with several measured peak depths of 0.75 inch. The brake surface heaters were energized and 45 minutes to 1 hour later, normal system operations were possible. The temperatures during this day ranged from 0°F to 17°F. Figure 9-1 shows some of the photographic documentation of this 2-day system-level test.

9.3 SYSTEM-LEVEL TESTS IN SNOW EVENTS WITH A WATER CONTENT OF 15 TO 30 PERCENT

Precipitations in the form of man-made snows with water contents of 15 to 30 percent were produced for system-level test operations on five separate occasions: January 8, 17, 18, 31, and February 25. The initial tests were conducted on the 8th of January, using the Otis test vehicle and a Duke shroud and debris guard installation. Three runs were performed with 0.75 to 2 inches of snow accumulation on the guideway. On the second run snow got behind the shroud and it was pushed up in the air. The shrouds and debris guards were removed for modification and a

4TH RUN IN SNOWSTORM, MELTING ON
BRAKE SURFACE WIDER THAN USUAL

5TH RUN, GUIDEWAY PARTIALLY MELTED AND SLUSHY

FIGURE 9-1. AUTOMATIC OPERATIONS IN CONTINUOUS SNOWFALL third run was performed without shrouds or debris guards. The vehicle speed was slowed during this run because of the amount of heavy wet snow that was pushed by the vehicle and the resulting operating characteristics without the shrouds and debris guards in place. Figure 9-2 shows the results of the system-level test runs on this particular day.

On the 17th of January, system-level tests were performed with four circulation runs of the vehicle into man-made snow accumulations. The first two runs were made with on-guideway snow depths of 0.5 to 0.75 inch and left the guideway very clean. The man-made snow production rate was increased and a total of 2 to 3 inches of snow with a moisture content of more than 30 percent was deposited on the guideway. Runs 3 and 4 were made, the vehicle coming to a stop at the end of run 4 in heavy wet snow and slush with a moisture content of over 50 percent. The wet snows on the guideway flying surface were being compacted by the vehicle to a depth exceeding 1 inch. The resulting increase in air gap and decrease in thrust caused the vehicle to lose speed. The debris guards were removed and modified to prevent the accumulation of snows on the guideway flying surfaces. Figure 9-3 shows photographic records documenting the results of the system-level test on January 17, 1980.

On January 18, 1980, snowmaking operations were commenced at 5:35 in the morning. The vehicle was circulated through the snow accumulations in the test area for a total of five runs, removing snow accumulations ranging from 1 to 1.5 inches each time. All runs were conducted without any adverse effects as the vehicle was successfully operated through a simulated winter storm event of wet snows with a moisture content of 25 to 35 percent and a total off-guideway accumulation of 7 to 8 inches. After completion of the last circulation run, the vehicle was operated in the automatic mode through the test area and performed an emergency brake stop, with normal deceleration levels and stopping distances. Figure 9-4 shows the photographic documentation of the system-level vehicle circulation tests performed on the 18th of January.

1ST NORMAL VEHICLE RUN IN 1980, USING
NON-WINTERIZED SHROUD

NOTE SNOW BEHIND SHROUD ACCESS DOOR FORCING IT
OPEN. SHROUD WAS MODIFIED AFTER THIS RUN

FIGURE 9-2. VEHICLE SYSTEM-LEVEL TEST IN MAN-MADE SNOW

VEHICLE CIRCULATION ON 1-17-80
REMOVING INITIAL SNOW COVER

CLEARED GUIDEWAY AFTER ABOVE RUN

FIGURE 9-3. SYSTEM-LEVEL TESTS, 1-17-80

VEHICLE REMOVING WET SNOW IN
SYSTEM-LEVEL TEST

GUIDEWAY AFTER ABOVE RUN

FIGURE 9-4. SYSTEM-LEVEL TESTS IN WET SNOW

Before the Otis test vehicle was operated in another system-level circulation test, 3 severe man-made snow events were produced with total peak accumulations of 55 inches and moisture contents of 30 to 45 percent. This produced off-guideway snowbanks of 40 to 48 inches in height, enclosing the power rails except for the contact surfaces.

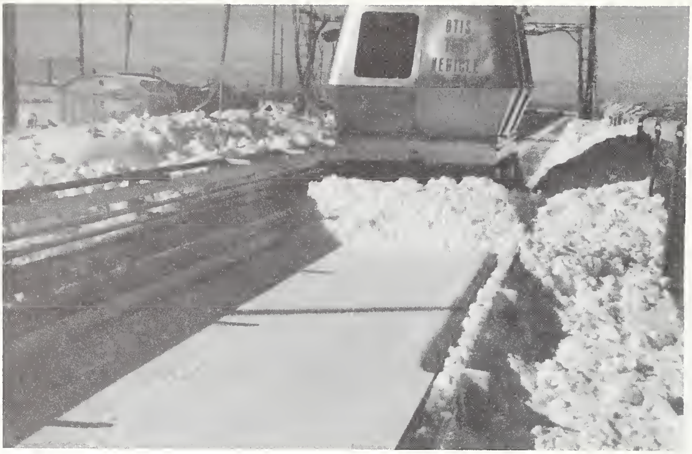
The vehicle was circulated through the test section four times on the 31st of January, removing 1 to 2 inches of snow (man-made) each time. When the vehicle returned through the test section after removing snow on run 2, a power collection fault occurred due to the ice and snow that was incompletely cleared by the snowplow the day before. A ridge of ice and hard snow was left along the edge of the bottom power rail, which demonstrated the need for modification of the snowplow to prevent such an occurrence in the future. The fault was corrected and the system restored in 10 minutes to make the remainder of the automatic runs. After the last automatic pass through the test area the vehicle was emergency braked into braking surfaces that had snow accumulation on most of the surface area. The brake surface heaters were energized and this produced a melting on the brake surface under the snow accumulations. Emergency braking deceleration levels and stopping distances were normal for wet emergency brake stops. Figures 9-5 and 9-6 show the photographic documentation of the system-level test.

Additional system-level circulation tests were conducted on four other specific test days during the 1979-80 test program with similar results. Snows with water contents that exceeded 30 percent were produced using the snowmaking equipment. Some of these snows were extremely wet, with a water content of 45 percent. Continued automatic operations through several sequential winter storm events would likely require the removal of the snow spoil or snowbanks located on outside edges of the guideway area.

NIGHT RUN AFTER SEVERAL SIGNIFICANT
MAN-MADE SNOWSTORMS

SYSTEM-LEVEL RUN IN MAN-MADE SNOW, OFF-GUIDEWAY SNOW
ACCUMULATIONS WERE 40 INCHES IN LAST WEEK

FIGURE 9-5. SYSTEM-LEVEL TESTS AFTER SIGNIFICANT
MAN-MADE SNOWSTORMS



VEHICLE CIRCULATION ON 3RD RUN, 1-31-80

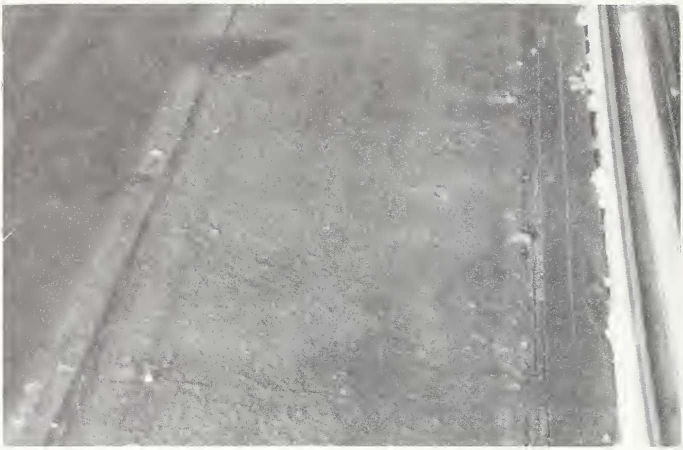
1 TO 1.5 INCHES ON GUIDEWAY SURFACE

FIGURE 9-6. SYSTEM-LEVEL TESTS IN MAN-MADE SNOW

9.4 SYSTEM-LEVEL TESTS IN GLAZED AND RIME ICE CONDITIONS

The Otis test vehicle was operated in glaze and rime ice conditions on eight different occasions during the 1979-80 winter season. The icing conditions were produced using man-made methods, coating the guideway components with water and allowing it to freeze. On 3 consecutive days, 10 automatic circulation runs were made on glaze ice with up to 1.75 inches of off-guideway accumulations. The ice surface ranged from very rough, with hunks of frozen snow and ice in the surface, to a smooth, almost glass-like appearance. The maximum depth of ice coating that remained on the surface was 0.5 inch as the vehicle debris guard removed some ice on each run. On the last day the latter runs removed almost all the ice on the guideway surface due to the above-freezing temperatures. The heated brake surfaces produced normal emergency brake rates during all these runs. On the vehicle's last run through the test area, 50 percent of the total ice accumulations, water, slush, and ice chunks were removed ahead of the vehicle debris guards completely clearing approximately 50 percent of the guideway surface area of ice accumulations. This left the guideway with a mottled appearance and 3/8-inch-thick discontinuous ice accumulation on the flying surface. No difficulties were encountered in the operation of the vehicle through any of these icing conditions. The propulsion thrust power demand attributable to the icing conditions on the guideway varied from 20 percent of the total thrust available as a maximum to an unmeasurable increased amount, depending upon the actual guideway surface conditions. Figure 9-7 shows vehicle operations during these 3 days of ice conditions.

Three additional test days of icing conditions were produced on the 1st of February, the 29th of February, and the 12th of March. All ice accumulations that were produced presented no problem to vehicle operations. Of an interesting note were the rime ice conditions that were produced on the 12th of March. They were negotiated successfully on four different test runs, with the total guideway accumulation varying from 0.25 to 0.5



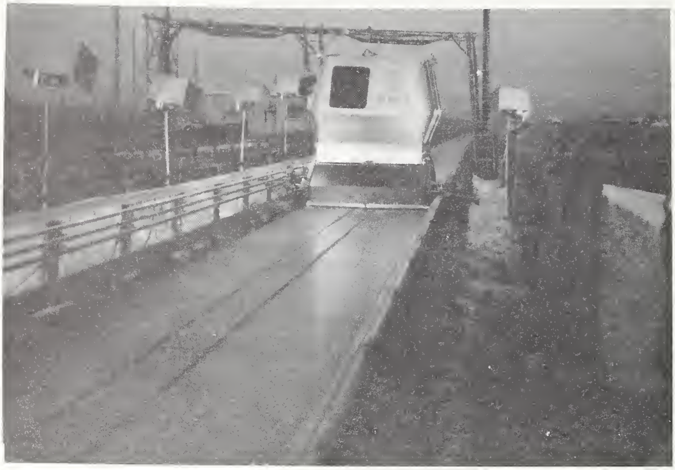
CLOSE-UP OF ICE COVERING ON
GUIDEWAY FLYING SURFACE

CONTINUATION OF ICE RUNS ON 1-24-80,
ICE THICKNESS 0.5 INCH

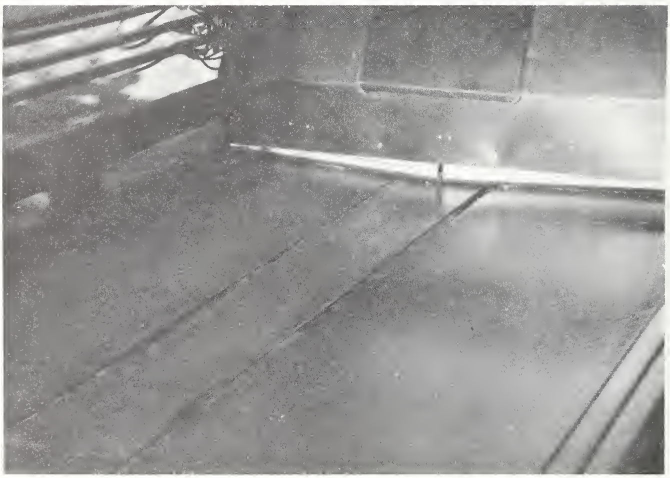
FIGURE 9-7. SYSTEM-LEVEL TESTS IN GLAZE ICE inch of rough ice. The last circulation run of the vehicle produced a discontinuous ice-coated surface and included a test of the emergency brake system. The braking surfaces were wet and produced normal deceleration levels and stopping distances. The vehicle debris guards removed a significant quantity of ice layers and slush ahead of the vehicle during this run, and after the emergency brake stop, the vehicle was reset in automatic mode and continued through the test area, cleaning additional loose ice and slush from the guideway surface. Figures 9-8 and 9-9 show these vehicle operations in rime ice and the emergency brake stop. During all of the system-level operations conducted in icing conditions no difficulty or operating limitation was ever encountered.

9.5 LOW-TEMPERATURE OPERATION OF SYSTEM-LEVEL TESTS

On four different occasions during the winterization test and demonstration program, the Otis test vehicle was operated in temperatures below $0^{\circ}F$ in the automatic mode. The automatic operations were performed at various line speeds and under varying precipitation conditions. No limiting effects were noted during vehicle operations at these low temperatures. Some small effects were noted and included the stiffening of air suspension system air pads and the stiffening of the elastrometric components in the vehicle suspension systems. The initial vehicle cab temperatures at vehicle start-up were outside the range desired for passenger comfort, but rose to normal levels throughout the remainder of the test runs. On the Duke vehicle some system hardware and the automated control systems were designed for environments down to $0^{\circ}F$. In spite of these anticipated design limitations, the vehicle performed successfully during all tests that were conducted below $0^{\circ}F$. Some anomolies in longitudinal control, which produced some temporary degradation in ride quality at low temperatures, were noted. These degradations did not affect system operations and were not significant enough to cause discomfort to passengers.



VEHICLE CIRCULATION ON RIME ICE



CLOSE-UP OF DEBRIS GUARD UNDER WAY ON RIME ICE

FIGURE 9-8. SYSTEM-LEVEL TESTS ON RIME ICE

LATER IN THE MORNING
VEHICLE CIRCULATES ON RIME ICE

GUIDEWAY CONDITION AFTER ABOVE RUN

FIGURE 9-9. SYSTEM-LEVEL TESTS ON RIME ICE

One significant test day included vehicle operations with a minimum temperature of $-17^{o}F$, and an average low temperature of $-13^{o}F$ during vehicle operations. The vehicle performed these particular tests successfully while operating in automatic mode and performing the requested trip profiles. The vehicle suspension components, which hardened at these low temperatures, did produce degraded, but not uncomfortable, ride quality, but did not affect system-level operations.

10. FINDINGS AND CONCLUSIONS

10.1 VEHICLE

The OTIS-TTD Duke vehicle and the Otis test vehicle were operated in the winterization test and demonstration program to verify their winter weather operational capabilities. These capabilities were continuously observed and evaluated during the program. When limitations of vehicle performance occurred due to the imposed winter conditions, the vehicle limitation was reviewed and the susceptibility of a specific component or subsystem was then evaluated for solutions. These potential solutions were continually incorporated during the test program and this resulted in an upgrade of the total system performance in the winter conditions. With the specified winterization modifications Otis vehicles can be operated during the severe winter conditions the test program proposed.

Automatic operation of the vehicles and system are well within the capabilities of the winterized Otis system and is the preferred approach to handling the onset of severe winter weather events. This method allows the continued service and availability of the system while removing the accumulation of winter precipitations without necessitating passenger delays or additional maintenance costs. Vehicles can be operated automatically in snowstorms with accumulation rates of up to 2 inches per hour by vehicle circulation at 1/2-hour intervals. The snow types during this automatic operation can vary from dry snows (less than 15 percent moisture) to heavy wet slush (more than 45 percent moisture). In the event of heavy wet snowfalls, the resulting accumulations must be removed from the guideway before they are allowed to freeze to the guideway surface. This might mean that even though the accumulations would not reach the nominal 1-inch capability of vehicles operating in the automatic mode, this wet snow accumulation needs to be cleared sooner to prevent the buildup of irregular frozen accumulations on the guideway surface.

The increased vehicle power consumption, resulting from circulation through and the removal of snow accumulations occurring during a winter snowstorm event, averaged an additional 30 kilowatts per vehicle over all the snow and guideway conditions that were tested during the winterization program. Based on this information and a 2 to 3¢ per kilowatt-hour power cost, the total additional cost to expose a vehicle to an average winter snowstorm event can be estimated. In a severe winter snowstorm with snow falling at the rate of 2 inches per hour and continuing for 8 hours with a total accumulation of 16 inches, the vehicles would be circulated at 1/2-hour intervals, clearing 1 inch of snow from the guideway survace on each pass. The additional power consumption costs imposed by the snow accumulations in continuing vehicle circulation at 1/2-hour intervals during this snowstorm, would be $4.80 to $6.25 per vehicle for the 8-hour period.

The vehicle limitations encountered during the test program were corrected with negligible effects on system operations. Some events are pointed out as being of particular interest. The fall of wet heavy slush on a guideway surface must be removed (by normal vehicle circulation) prior to allowing these accumulations to freeze and adhear to the guideway surfaces. If freezing is allowed to occur, generally speaking, automatic vehicle operation is not possible and maintenance operations are required to remove the ice and frozen snow accumulations from the guideway surface. Ice accumulations in excess of 0.75 inch on the guideway surface are detrimental to vehicle operation. Accumulations of 0.75 inch were successfully negotiated during the winterization test program (increasing the propulsion motor air gap) but the reduction of vehicle thrusts with ice buildups in excess of 0.75 inch would leave the vehicle with little acceleration capability and increase the potential of becoming slowed or stopped during the winter conditions.

A vehicle limitation determined during the first season of operations was later corrected during the 1979-80 winter operations by the addition of and modification to the winterized capabilities of the test vehicle. This limitation was the inability to operate the test vehicle over discontinuous ice or frozen snow accumulations on the guideway. This particular set of conditions was performed several different times during the second winterization season without any noted difficulties. The improvement in this area resulted, specifically, from the modifications to and proper installation of the winterization vehicle shrouds and debris guards.

The vehicle-mounted snowplow proved capable of removing any of the snow accumulations that were placed on the Otis test-track guideway. Even snow accumulations of up to 25 inches were removed through the use of the snowplow, although the deepest accumulations required repetitive runs. The snows produced from the snowmaking equipment typically had higher moisture contents than specified for use during the test program. Power collection by the vehicle during the snowplow operations experienced difficulties several different times and specific recommendations need to be made in this area to remove the potential of vehicle power interruption due to snowplow operations. The vehicle-mounted snowplow design cannot be generalized for any guideway/vehicle installation but must be specifically determined, based on the guideway equipment installed and the vehicle guideway interfaces.

Vehicle operations in snowstorm events with winds in excess of 40 mph would not seem to be advisable based on the experience Otis has had at the Denver test site. Although we were not able to perform this type of test during the winterization test program, these storms generally result in such a disruption to normal city or county level services as to not allow system maintenance or operational personnel go get to their work stations. Also if there exists the possibility of a vehicle becoming disabled on the guideway during these particular snowstorm events, system operations should be suspended to avoid vehicle-clogged guideways and passenger rescue, which would significantly complicate the snow removal process.

For instance, the Denver test track, with its rural location (approximately 7 to 8 miles from any significant urban development), becomes completely isolated during such snowstorms as that which occurred on the 20th and 21st of November, 1979. This snowstorm event, with winds in excess of 50 mph, isolated the test-track site and the surrounding area for 6 days until roads could be opened and access achieved to the site.

Critical subsystems that were identified during the test program were modified for winterization operations and the results of their performance and modifications have been herein described. The vehicle lateral guidance assemblies were provided with a flexible rubber boot which was installed over the sliding suspension bearing assembly. This provided protection from winter precipitations for the sliding bearing. The lateral guidance units performed successfully throughout the test program with no detrimental effects measured or identified about the lateral guidance tires. The suspension spring rates of the elastrometric components in the lateral guidance assemblies were increased during extremely low-temperature operations (-17°F). Systems that would operate in these low temperatures need to have low-temperature design considerations taken during the design stage of the system equipment.

The vehicle-mounted route switching and retention was modified for winterization operations by adding a flexible rubber boot to cover the sliding arm where it would enter the fixed sliding bearing assembly. This flexible boot protected the switching mechanism from the accumulations of winter precipitations, preventing those precipitations from interfering with the switching of this mechanism. The actuator with electrical and mechanical interlocks is located between the vehicle body and chassis. An environmental closeout was installed on the Duke vehicle to prevent winter precipitations from entering this particular area and affecting the operation of the switching mechanism. The Duke vehicle route switching was not compatible with the Denver test-track equipment configurations and, therefore, was not tested dynamically. For one test conducted in 1979 (using the Duke vehicle), accumulations of heavy wet snow and slush were placed on the vehicle to determine the effects on the vehicle components. This accumulation of slush built up on the boots that protected the sliding switch arms and after a period of time these wet accumulations froze. The freezing of these accumulations in an extended flexible boot resulted in significant switch arm actuation loads. The flexible boots for these particular arms should include a minimal level of heating to prevent the buildup of frozen accumulations.

The vehicle power collection winterization modifications were primarily concentrated in heating the guideway distribution rails. This proved to be quite effective during all forms of winterization precipitations. The only modification to the vehicle power collection assembly was the addition of low-temperature silicone lubricants to the pivot areas of the power collection arms. During vehicle snowplow operations, it became apparent that the power collection mechanism could easily be disturbed by the throwing of snow accumulations from the guideway. The location of the power collector assembly on the vehicle put it directly underneath the snowplow wing and there it collected much of the spilled snows from the snowplow, and it ran directly into any snow accumulations that were not removed by the plow in the area of the power distribution rails. As a result of snowplow tests, two recommendations are made for power collectors during vehicle snowplow operations. The snowplow should be located at the opposite end of the vehicle away from the power collection assembly, thereby reducing the effect on this power collection assembly from the spillage of snows from the snowplow blade. For snowplow operations, power collector shrouds should be provided for the top and leading edge of the power collector assembly, thus protecting the mechanism from direct impact with snow accumulations that might remain in the guideway area.

The test-track power distribution rails are located approximately 6 inches outboard of the suspension rail with the top power rail approximately 25 inches above the guideway flying surface. The relocation of these power distribution rails in a DPM deployment will be considered. The optimum location, from a winterization standpoint, is a low height profile with guideway walls providing an enclosed or partially-enclosed area for the distribution rails with the contact face of the distribution rails being oriented downward in a horizontal plane.

The vehicle communication antenna was an environmentally-sealed unit. This was not modified in any way for winterization operations and was successfully operated during the winterization program.

The vehicle vertical air suspension system air pads, 12 of which are installed on the underside of the Otis test vehicle, were not modified for winterization operations except that vehicle shrouds and debris guards cleared the guideway surface prior to operating the air suspension pads. If winterization conditions typical of those tested and performed during the 1979-80 winter season were anticipated for DPM deployments, the vertical air suspension system suspension blower capacity could be increased, providing higher air flows to the air suspension pads and materially extending the operational capabilities of the OTIS-TTD vehicle. No detrimental effects were encountered in the vertical air suspension system with the suspension blowers, dump valves, manifolds, or air suspension pads except to the extent that the pads were exposed to rough and irregular guideway surfaces which decreased their operating efficiency.

The Otis vehicle contains a secondary vertical suspension system that is located between the chassis and body providing an isolation between these components. This system is designed to decouple vibrations produced in the vehicle chassis from the passenger compartment. These secondary suspension assemblies utilize an elastrometric spring. During cold weather operations (-17°F) these elastrometric properties were changed and the mounts became hard, allowing the coupling of additional vibrations to the body. A DPM deployment location experiencing these extremely low temperatures should have a material for the secondary suspension shear-mounts that exhibits good low-temperature operating characteristics.

The vehicle chassis shrouds and debris guards that were installed for the winterization test and demonstration program were Duke equipment that initially was not modified. As the vehicle was operated in the various winter conditions, these shrouds and debris guards were modified as necessary to provide optimal vehicle performance. Once the modifications to the shrouds and debris guards were completed, the vehicle circulation through guideway winter precipitation accumulations was significantly improved to the point where no limitations were demonstrated in vehicle operation.

The vehicle-mounted tachometers, which determine the actual vehicle speed, are an environmentally-sealed unit. They are mounted on the vehicle lateral guidance assembly and run on the guideway suspension rail. The guideway suspension rail was heated during the winterization test program to provide vehicle ground contact reliability and adequate traction for the tachometer drive wheel. The tachometers were enclosed in a shroud which adequately protected them from winter precipitation accumulations and impact with the accumulations that were built up in the guideway.

Vehicle block signal collection was accomplished in a fashion similar to the power distribution collection, using the same rail and power collector hardware. The signal rail was heated, providing a reliable contact surface for the signal brush. This signal collection capability was demonstrated during the program as being reliable and successful.

The vehicle doors were tested during the winterization program with the only effect being the slower door times experienced under extremely low temperatures. In all cases the doors operated successfully and did not influence the vehicle or system operations.

Deployed DPM winterized vehicles should be inspected at more frequent intervals than those for vehicles operating in normal weather conditions. This frequent inspection should verify the integrity of the winterization modifications to the vehicle, assuring that the advent of severe winter weather conditions will not influence system operation and the vehicles will operate reliably. Should vehicle system-level operation be lost during a winter snow event, an OTIS-TTD vehicle equipped with the winterization snowplow can be used to remove 15 to 25 inches of snow accumulation from the guideway under manual control. The snow accumulations will be removed sufficiently with 2 or 3 passes of the vehicle-mounted snowplow, and system-level operations can be resumed as soon as heated guideway braking surfaces allow normal emergency braking deceleration rates. These snow removal vehicles equipped with a vehicle-mounted snowplow can be provided with increased air suspension system capacities and increased propulsion thrust capabilities to further extend the clearing capabilities of the snowplow.

10.2 GUIDEWAY

The OTIS-TTD Denver test-track guideway was equipped with representative Duke hardware. This guideway installation was used to verify the winterization operation of the OTIS-TTD system during severe winter weather conditions. The guideway was modified for winter weather operations by placing resistance wire heaters in the concrete braking surfaces to heat these surfaces and remove snow and ice accumulations to retain the integrity of the emergency braking system. These resistance heater wires adequately removed all snow and ice accumulations that were selectively applied during the test program. The time required after the advent of winter precipitations to assure an unfrozen emergency brake surface was from 1 to 1.5 hours, dependent upon the snow and ice conditions, the ambient temperature, and wind conditions. Resistance wire heating was also installed in the guideway power distribution rails, providing the heat necessary to raise the temperature of these rails above freezing, preventing the accumulation of snow and ice in the rails from interrupting vehicle power collector contact. The guideway signal rail was heated using a similar method to assure contact by the vehicle-mounted signal collector and maintaining vehicle contact with the fixed block wayside safety control system. The dual-purpose guidance and grounding rail was heated to assure vehicle ground continuity during winter precipitations.

The guideway flying surface areas had an ice-mitigating hydrophobic coating applied to assist the removal of ice and frozen deposits from the guideway flying surfaces. This material had a significant effect on preventing or reducing the adhesion of frozen accumulations to the guideway surface. In the 1979-80 season of the program, an Otis standard concrete sealer was used in place of the hydrophobic coating. This particular concrete sealer, known as Achrychlor, is a chlorinated hydrocarbon chain suspended in a Toulene agent. This Achrychlor sealer performed almost as well as the hydrophobic coating in reducing ice adhesion characteristics at a significantly less cost.

Guideway heating in the recommended areas for the OTIS-TTD guideway configuration includes the power distribution rails, the signal rail, the vehicle ground and guidance rail, and the emergency brake surfaces in the guideway slab. The heating levels required are based on tests performed during the winterization program. The signal rail heating level should be 12 watts/ft. The power distribution rail heating level should be 9 watts/ft per rail. The ground rail heating level should be 20 watts/ft. The emergengy brake surface heating level should be 23 watts/ft. This results in a total guideway heating requirement of 105 watts per linear foot of guideway, or 554 kilowatts per mile. Based on current electrical power costs of 2 to 3 cents per kilowatt-hour, the total cost for heating the Otis DPM guideway to assure reliable and continuous system-level automatic operations for the typical scenario of an 8-hour winter snow event would range from $89 to $133 per mile, or $11 to $16 per mile per hour.

An enclosed location for power rails and signal rail in a DPM guideway installation is recommended to provide reduced profile heights of the power rail stack, improving the removal of snows from the guideway surface. Some potential improvements in power rail installation and insulative covers should also be investigated. This could include the relocation of the contact faces of the power rails in a horizontal axis with the contact surfaces pointing downward and the installation of a closed-face power rail insulator/cover. This closed-face insulative cover would have the potential of reducing the heating requirements for both the power rails and signal rail.

During all of the severe winter weather conditions experienced during the winterization test program, no damages occurred to any of the guideway-related equipment. This included the impacts of high winds, extremely cold temperatures and the advent of a winter storm event which placed accumulations of snow in the guideway to 4 feet in depth. In one specific instance, the high winds associated with a winter storm blew over the winterization photographic observation tower. These winds reached peak gusts of 70 to 75 mph.

Two extensive natural snowstorms occurred during the winterization test and demonstration program. The first occurred during the 1978-79 season and deposited 2 to 3 feet of snow accumulation (primarily by drifting conditions) in the guideway area. A second storm that occurred during the 1979-80 winter season at the end of November produced extreme snowfalls and drifting conditions with 3 to 4 feet of snow accumulated in the guideway area. These two snowfalls were removed by the maintenance equipment, assisted by hand operations. The vehicle snowplow was not operationally available for either of these two natural snow events. The latter snow event was removed from the guideway approximately 5 days after the initial snowfall occurred because access could not be achieved to the test site. One hundred man-hours, including the use of the maintenance vehicle with the 42-inch snowblower unit, were expended to clear the test track of this 3- to 4-foot average accumulation of snow (2900 feet of total guideway). No damage to the guideway and related hardware due to the snowfall or the removal operations was noted. This type of snow accumulation caused by extensive drifting should be prevented in at-grade DPM installations by the use of snow fencing.

Man-made snow accumulations were placed on the guideway in significant accumulations at five different times. These accumulations of 9, 12, 15, 21, and 25 inches of man-made snow with moisture contents from 25 to 45 percent were removed by the use of the vehicle-mounted snowplow. This vehicle-mounted snowplow successfully removed all of the snow accumulations, frequently requiring more than one run to clear the winterization guideway section. After the snowplow removal, system-level operations were resumed on the guideway within 30 to 45 minutes. The vehicle power collection/guideway power distribution interfaces need further improvement to minimize their susceptibility to the snow accumulations removed by the vehicle-mounted snowplow. Disturbances to power collection on this snowplow vehicle resulting from snowplow operations had an effect on vehicle snow-removal operations on several occasions. Of the five heavy snow accumulations that were placed on the guideway during the vehicle snowplow testing, four exceeded the requirements of the test program, in either the required accumulated depth or the moisture content of the snows.

Ice accumulations were applied to the guideway and guideway hardware on seven different occasions. The ice formations varied from a simulated freezing rain, or glaze ice, to a sleet, or rime ice. These ice accumulations were successfully removed from the critical areas of the guideway by the guideway heating system, allowing system-level automatic vehicle operations. The production of freezing rain equivalent to off-guideway accumulations of 1 to 2 inches never produced in excess of 0.75 of an inch of accumulations on the guideway flying surfaces or reaction rail surface. This is a result of some of the freezing rain running off to lower areas (i.e., heated brake surfaces) and the continued operation of the vehicle over the surfaces allowed the vehicle-mounted debris guard to remove a certain amount of slush, water and partially-frozen accumulations from the guideway. The ice accumulations that did build up on the guideway surface were of little consequence to the automatic operation of the vehicle. The increased operational power requirements of 25 kw on ice resulted in a net cost increase of $4 to $6 per vehicle per 8 hours of operation at system-level circulation intervals of one-half hour. The 8-hour time period was used as a scenario based on a typical severe winter storm event of that duration.

No effects on the guideway-mounted communications antenna were noted either in subjective visual observations or as a result of recorded data. In a couple of cases during extremely heavy guideway snow accumulations and snowplowing operations using the vehicle-mounted plow, lateral deflections were created in the guideway communication antenna. These deflections resulted in variations of signal level that were recorded on board the vehicle. These variations in signal level were small, on the order of 7 percent of the automatic gain range of the communication receiver. Due to the passive nature of the guideway communications system and its ability to operate successfully without influences from winter precipitations, OTIS-TTD can offer the alternative of using this guideway communications network for vehicle safety control and signalling. This approach would eliminate the need for a guideway-mounted signal rail and the need for the heating of this rail, also eliminating the mechanical vehicle-mounted signal rail collector assembly (which is an item requiring service and maintenance on regular intervals). This would produce significant advantages to the user both in costs and reliability.

In conclusion, go guideway-related equipment limitations were identified as a result of the severe winter weather conditions imposed during the winterization test and demonstration program.

11. RECOMMENDATIONS

The test operation clearly indicates that the best operational scenario for the OTIS-TTD HOVAIR vehicle is to simply continue operations during the severe winter weather. Even in heavy ice or snowfalls, the debris guard will push the accumulations aside and the system will continue to operate. The vehicle is LIM propelled and not dependent on wheel traction for movement. Therefore, the vehicle can operate over accumulations of glare ice up to 1 inch thick. The debris guard and shroud can handle accumulations of snow up to 4 inches. For larger accumulations, it is necessary to use a vehicle equipped with a snowplow or snowblower. The snowplow will handle accumulations of approximately 14 inches at a speed of 20 to 30 fps. The snowblower will handle large accumulations, but at much slower speeds. The primary scenario of simply operating the vehicles during the severe weather is applicable to all potential locations in the U.S. The recommendation for the use of a snowplow or snowblower is site-specific and will depend almost entirely upon constraints imposed by the operating agency.

The complete enclosure of guideways in locations where deployments would be exposed to significant severe winter weather should be considered and reviewed in light of cost, performance, and aesthetic considerations.

APPENDIX A
WINTERIZATION PHOTOGRAPHIC RECORDS

APPENDIX A

WINTERIZATION PHOTOGRAPHIC RECORDS

Number	Date	Description
0001	11-21-79	Snow Storm, Test Site Inaccessible
0002		Test Equipment and Snowmaking Gear
0003	12-18-79	Snowmaking Gear Checkout
0004	1-07-80 1-08-80	Vehicle Snow Plow Operations Vehicle Circulation in Snow, Run #1
0005	1-08-80	Vehicle Circulation in Snow, Runs #2 & 3
0006	1-09-80 1-11-80	Snow Plow Fit Check, Heater Test Vehicle Run in Heavy Frost 1-14-80
0007	1-16-80	Two Circulation Runs Early Morning, Light Snow, Runs #1 & 2
0008	1-16-80	Two Vehicle Circulations, Runs #3 & 4
0009	1-17-80	Two Circulations, Runs #1 & 2, Early Morning, Light Snow
0010	1-17-80	Vehicle Circulations, Runs #3 & 4 and Stopped in 1½" Slush
0011	1-18-80	Vehicle Circulation, First Run
0012	1-18-80	Vehicle Circulation, Runs #2 & 3
0013	1-18-80	Vehicle Circulation, Last Run #4
0014	1-18-80 1-21-80	Vehicle After Circulation Vehicle Snow Plow Preparation
0015	1-21-80	Vehicle Snow Plow 10" Snow
0016	1-21-80 1-22-80	After Plowing Vehicle Plow 25" Snow, Run #1
0017	1-22-80	Vehicle Plow 25" Snow, Runs #2, 3, & 4
0018	1-23-80	Glaze Ice, Circulate Vehicle, Runs #1 & 2
0019	1-23-80 1-24-80	Glaze Ice, Circulate Vehicle, Run #3 Glaze Ice, Circulate Vehicle, Run #1

Number	Date	Description
0020	1-24-80	Glaze Ice, Runs #2 & 3, Melt Snow Banks, Wash G.W.
0021	1-25-80	Glaze Ice, Circulate Vehicle, Runs #1 2 & 3
0022	1-25-80	Glaze Ice, Circulate Vehicle, Runs #3, 4 & 5 Hose Fault
0023	1-25-80	Water Hauling, Melting Snow Bank
0024	1-30-80	Vehicle Snow Plow, First Set, 21" Depth
0025	1-30-80	Vehicle Snow Plow, Second Set, 21" Depth
0026	1-31-80	Vehicle Circulation, Snow, After Big Plow, Runs #1 & 2
0027	1-31-80	Circulation, Snow, Run #3, 2 Passes
0028	2-01-80	Vehicle Circulation, Ice, Runs #2, 3 & 4
0029	2-07-80	Vehicle Circulation, Natural Snow to Ice to Slush
0030	2-07-80	Vehicle Circulation, Ice and then Natural Snow
0031	2-08-80	Natural Snow - 12" Normal Vehicle as Snow Removal
0032	2-11-80	Vehicle Snow Plow Mod 3
0033	2-12-80	Impact Vehicle with Snow, Early
0034	2-12-80	Vehicle After Impact Test
0035	2-12-80	Impact Vehicle & Run Normal Operations
0036	2-15-80	End of Vehicle Snow Plow Run, 15" Snow, with Power Collector Failure
	2-25-80	Vehicle Circulation, Very Wet Snow, 1 Run
0037	2-29-80	Ice the Vehicle & Automatic Run
0038	3-13-80	Rime Ice, Vehicle Circulation, Runs #1, 2 & 3

Number	Date	Description
0039	3-13-80	Rime Ice, Vehicle Circulation, Runs #4 & 5, Emergency Brake
0040	2-29-80 3-01-80	Ice on Vehicle & Automatic Run Natural Snow, Snow Removal with Normal Vehicle
0041	3-17-80	Vehicle Circulation, 25% Snow, Signal Rail, Runs #1 & 2
0042	3-17-80	Vehicle Circulation, 25% Snow, Signal Rail, Runs #3 & 4
0043	3-17-80	Vehicle Circulation, 25% Snow, Signal Rail, Run #5, Striking the Colors
0044	3-24-80	Heater Test, Last, Temperature Profiles

APPENDIX A

1980 WINTERIZATION VIDEO TAPE RECORDS

Tape #1 1-14-80 000-390

Camera check-out and pretest over view.
Temperature rise test on guideway equipment.

Tape #2 1-7-80 and 1-8-80

000-105	Snow gear prep.
105-570	Snow making OPs.
570-610	Snow plow run checkout
610-730	More snowmaking on guideway
730-740	Snowplow TEST run (N-G)

Tape #3 1-16-80

000-075	Snow making ops.
075-110	Run #1, circulation 1-1½" snow
110-220	Snow making ops.
220-235	Run #2, Circulation ½-1" snow
235-282	Snow making ops.
282-295	Run #3, circulation 3/4-1" snow
350-385	Run #4, circulation

Tape #4 1-17-80 and 1-18-80

000-075	Snow making ops.
075-130	Run #1, circulation 3/4-1" snow
130-200	Snow making ops.
200-235	Run #2, circulation 3/4-1" snow
235-310	Run #3, circulation 3/4-1" snow with 3-5 inches heavy slush, several passes
310-380	Run #4, circulation heavy slush 1-2" snow getting under vehicle and stops
380-435	1-18-80 Run #1, circulation 1-1¼" snow
435-453	Manual pass, Run #2
453-495	Run #3, circulation 1-1½" snow
495-613	Snow making ops.
613	Run #4 no video 1-1½" snow
613-684	Run #5, circulation 1-1½" snow very wet, 2nd pass
684-710	Emergency brake 1 stop, brake surface heaters off

Tape #5

000-130	Snow making ops.
130-260	Vehicle snowplow ops. 12" snow depth
260-350	Vehicle emergency brake test after snowplowing
380-480	Vehicle snowplow ops. 21" snow depth, 3 runs
480-540	System level test 1/4" glaze ice

Tape #6 1-24-80 and 1-25-80

000-120	Ice on guideway before run
120-172	Run #1, circulation, ¼-1/8" ice
172-273	Run #2, circulation, ice another layer
273-287	Run #3, circulation, ice smooth
287-308	1-25-80 Run #1
308-331	E.B. stop on ice heaters on
331-610	Good view of water freezing
610-630	Run #3, circulation, ice and slush
630-645	Run #4, circulation, ice, slush, water
645-695	Nothing
695-723	Run #5, circulation, ice, slush, water hose fault
723-752	Run #6, circulation, mostly slush and water - Additional passes removed almost all ice from G.W.

Tape #7 1-30-80

000-080	Snow plow Run #1, 85'
080-120	Snow plow Run #2, another 40'
120-250	Reset veh. circuit breaker - etc.
250-270	Snow plow run #3, another 30'
270-555	Reset veh. again, clear snow from power collector
555-600	Snow plow Run #4, clear completely and a couple of additional passes
600-620	Auto run with plow still on

Tape #8 1-31-80 2-1-80, 2-7-80, 2-8-80

000-043	Run #1, circulation, 2" snow
043-091	Run #2, circulation, 1-2" snow, power fault
091-200	Run #3, circulation, 1½-2" snow, several passes
200-283	Ice the guideway
283-295	Run #1, 2-1-80, circulation, ice
295-332	Run #2, circulation, ice
332-396	Run #3, circulation, ice
396-427	Run #4, circulation, ice
427-490	2-7-80, circulation, run #1, ice glaze with natural snow ½"
490-520	Run #2, circulation, snow, slush, ice
520-585	Run #3, circulation, snow, slush, ice spots
585-615	Run #4, circulation, snow, slush and extra pass
615-705	2-8-80 Run #1 3-5" natural snow with 12½ drifts, 12% snow, ice 3/4 - 1½ thick on guideway

Tape #9 2-11,2-12 ,2-15,2-25,2-29-80

000-180	Snow plow runs, 10" snow
180-365	Impact vehicle with snow, auto runs after and E.B. stop 2-12-80
380-550	2-15-80 snow plow 3 runs 12-15" snow - additional passes with plow
550-630	2-25-80, circulation, wet snow, only 1 run
630-705	2-29-80, ice the vehicle, run auto, E.B. stop, no audio

Tape #10 3-13-80, 3-17-80

000-224	Vehicle circulation, rime ice, runs 1-6, emergency brake, brake loose ice
224-360	3-17-80 vehicle circulation in snow over ice - 5 runs in ¼-1" snow each

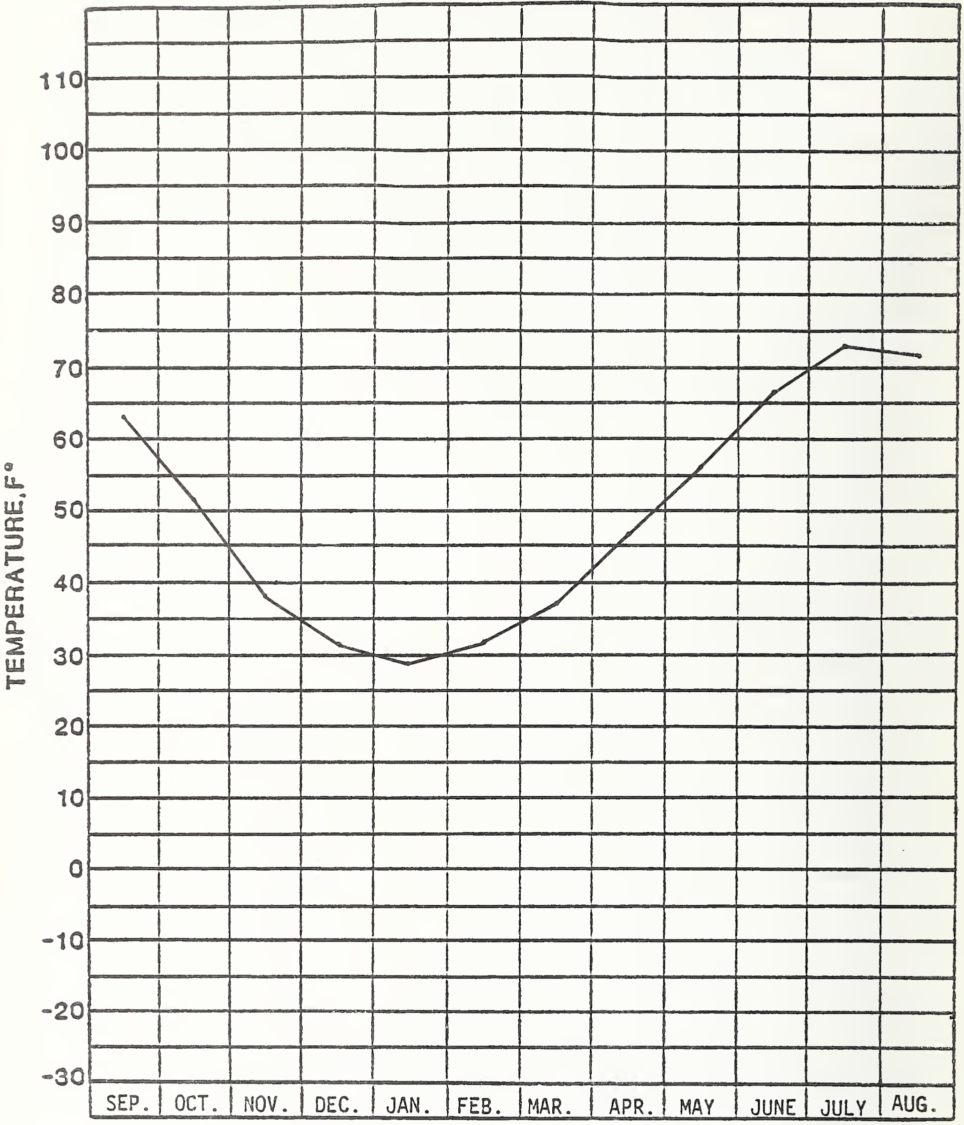
Tape #11

Highlights of Winterization Test Program

APPENDIX B

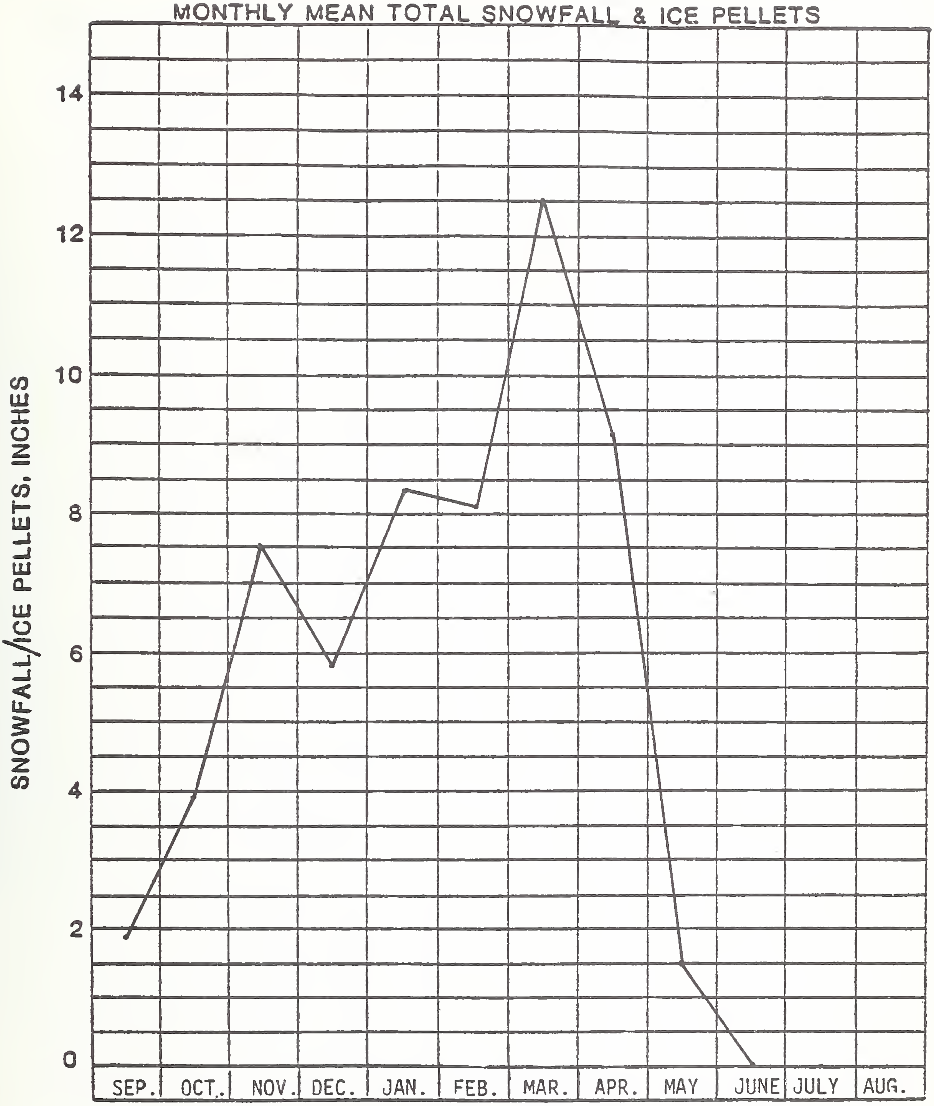
WEATHER DATA

MONTHLY MEAN TEMPERATURE *

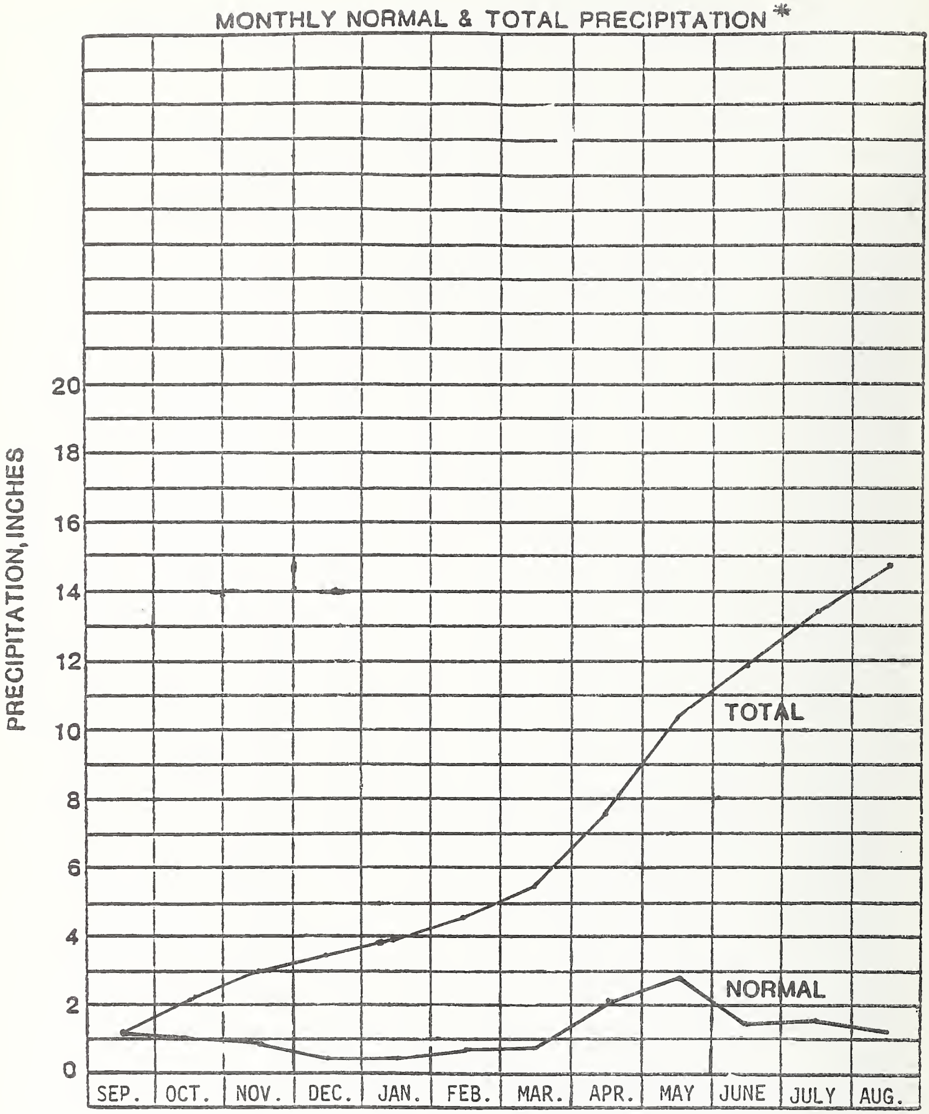


* CLIMATOLOGICAL STANDARD NORMALS (1931 - 1960)

DENVER

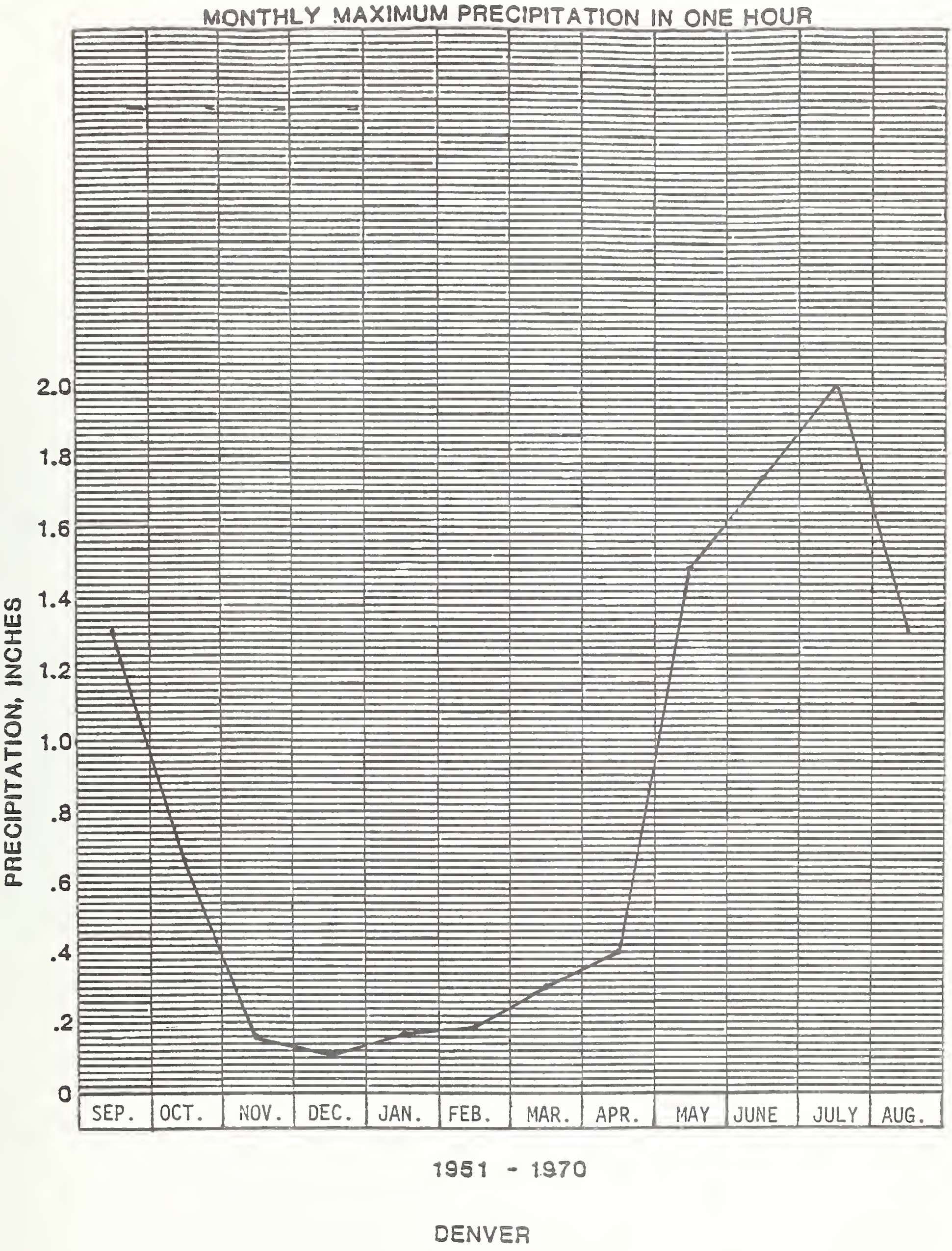

MONTHLY MEAN TOTAL SNOWFALL & ICE PELLETS
SNOWFALL/ICE PELLETS, INCHES
14
12
10
8
6
4
2
0
SEP.
OCT.
NOV.
DEC.
JAN.
FEB.
MAR.
APR.
MAY
JUNE
JULY
AUG.

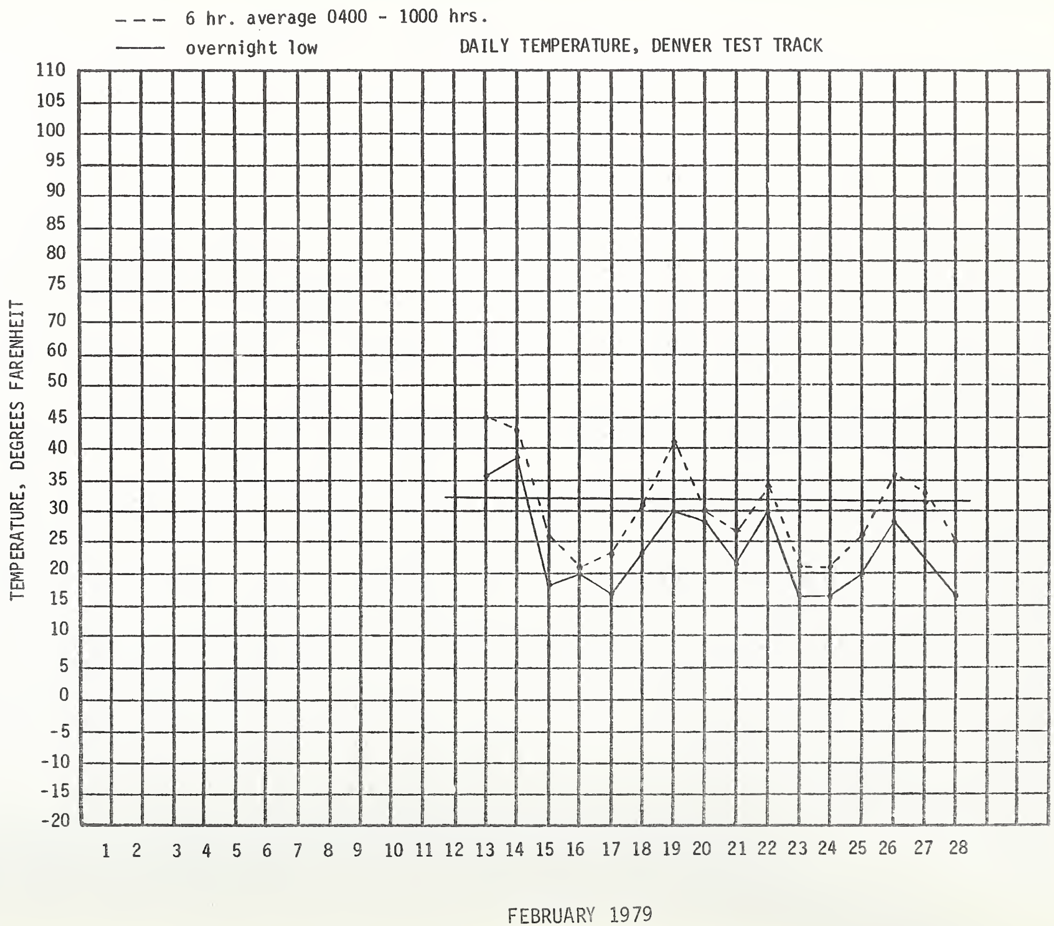
DENVER



* CLIMATOLOGICAL STANDARD NORMALS (1931 - 1960)

DENVER


MONTHLY MAXIMUM PRECIPITATION IN ONE HOUR
PRECIPITATION, INCHES
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
SEP.
OCT.
NOV.
DEC.
JAN.
FEB.
MAR.
APR.
MAY
JUNE
JULY
AUG.
1951 - 1970
DENVER



--- 6 hr. average 0400 - 1000 hrs.
—— overnight low
DAILY TEMPERATURE, DENVER TEST TRACK
TEMPERATURE, DEGREES FARENHEIT
110
105
100
95
90
85
80
75
70
60
50
45
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28
FEBRUARY 1979


- - - 6 hr. average 0400 - 1000 hrs.
—— overnight low
DAILY TEMPERATURE, DENVER TEST TRACK
TEMPERATURE, DEGREES FARENHEIT
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
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-15
-20
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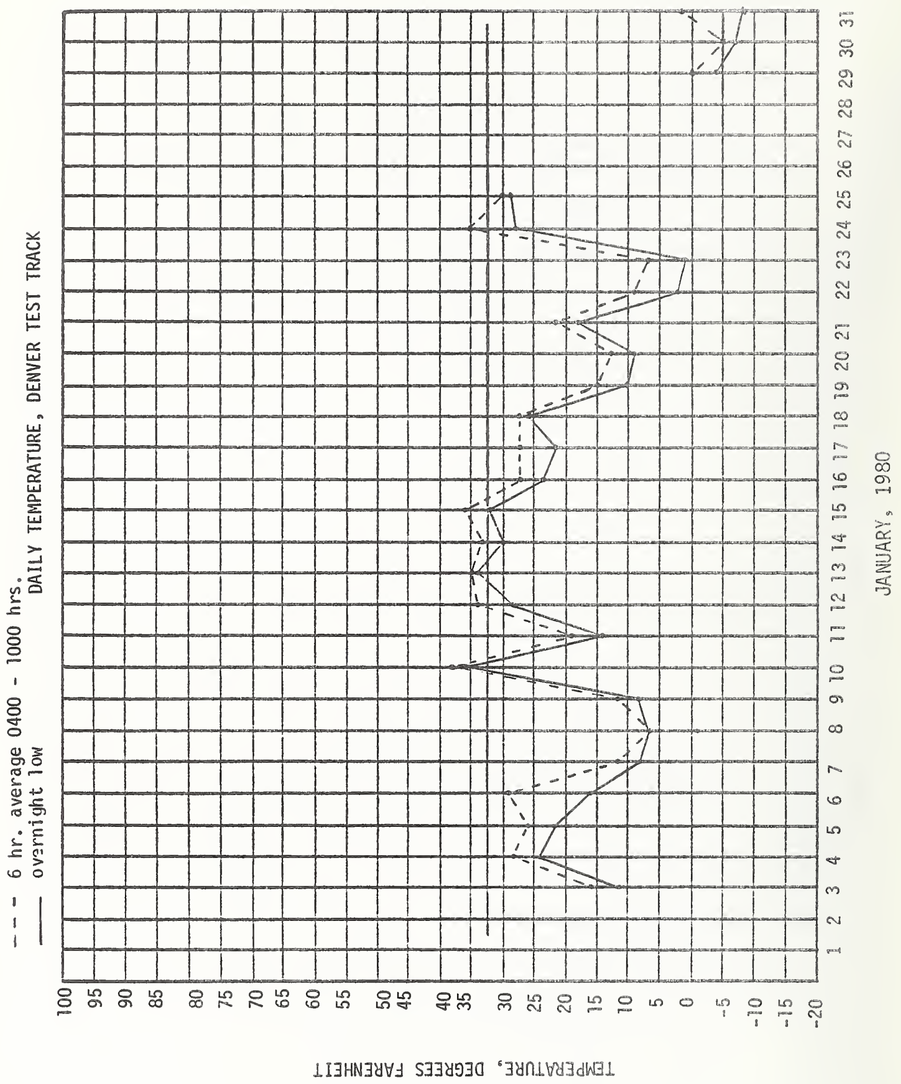
MARCH, 1979



- - - 6 hr. average 0400 - 1000 hrs.
—— overnight low
DAILY TEMPERATURE, DENVER TEST TRACK
TEMPERATURE, DEGREES FARENHEIT
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
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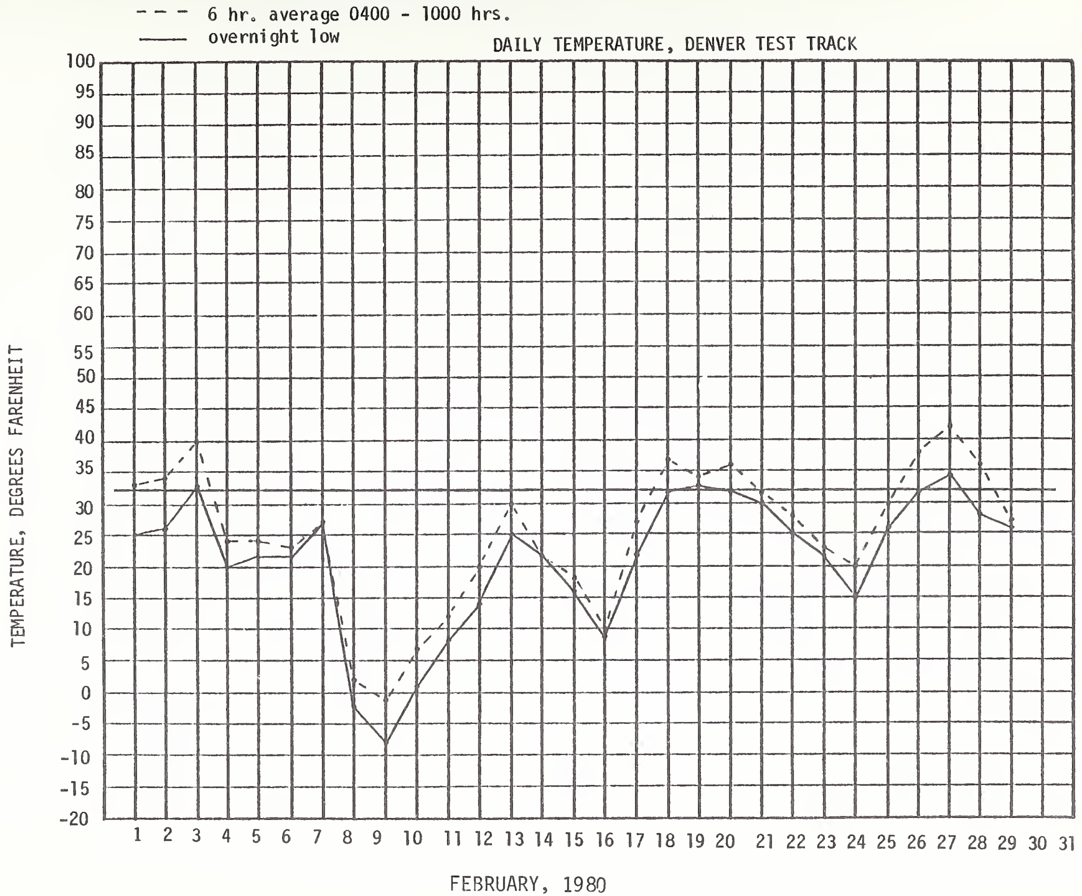
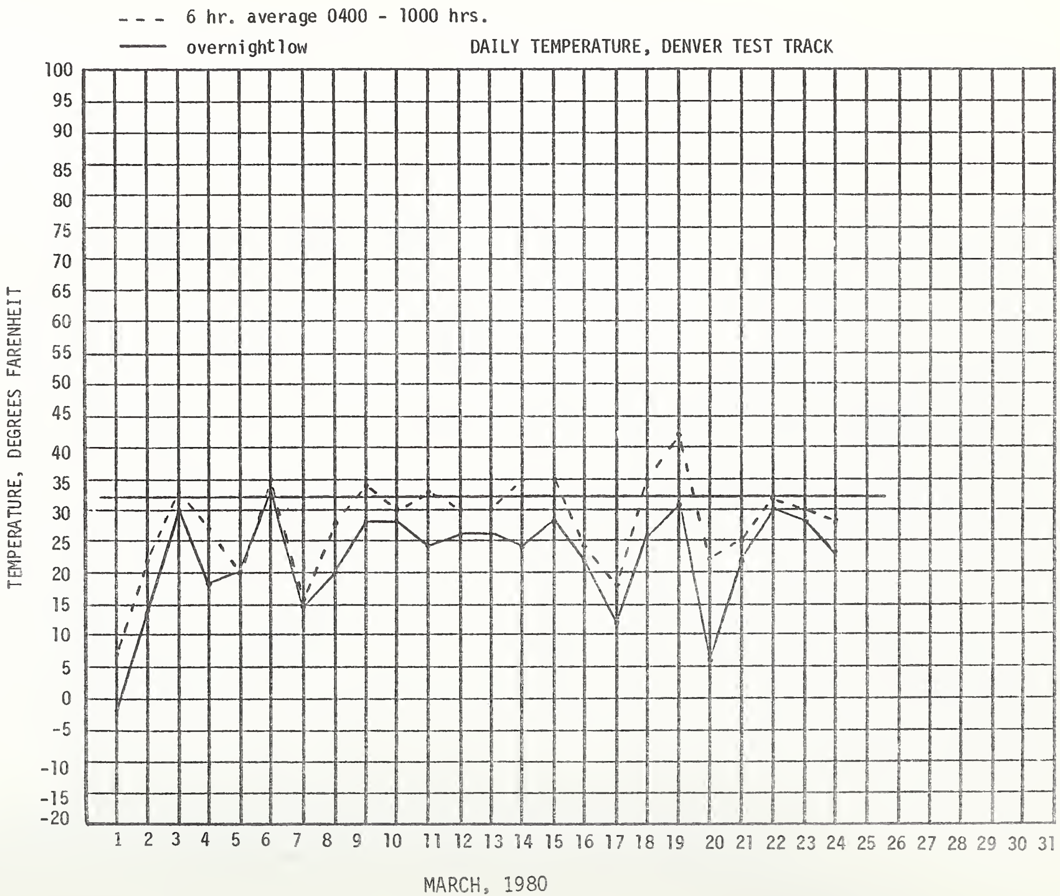
0
-5
-10
-15
-20
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
JANUARY, 1980



- - - 6 hr. average 0400 - 1000 hrs.
—— overnight low
DAILY TEMPERATURE, DENVER TEST TRACK
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
TEMPERATURE, DEGREES FARENHEIT
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
FEBRUARY, 1980



- - - 6 hr. average 0400 - 1000 hrs.
—— overnightlow
DAILY TEMPERATURE, DENVER TEST TRACK
100
95
90
85
80
75
70
65
60
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45
40
35
30
25
20
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10
5
0
-5
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TEMPERATURE, DEGREES FARENHEIT
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
MARCH, 1980

APPENDIX C

REPORT OF NEW TECHNOLOGY

There were no patentable inventions or discoveries resulting from this work. The contractor did, however, fabricate snow removal equipment such as plow blades, shrouds, and heaters and developed winterization techniques and operating strategies which will benefit the automated transit industry when severe winter climate deployments are considered. Effective winterization procedures and techniques will help provide reliable winter performance characteristics of AGT systems at reduced operating costs.

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