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The opinions presented in this paper are those of the Council of Governments Metrorail before-and-after study staff.

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A Radio-Frequency Deicing System for Third Rails

RICHARD KWOR

ABSTRACT

A radio-frequency (RF) deicing system for third rails has been proposed. It consists of an RF generator, transmission lines, a work coil, and a mechanical scraper, all mounted on a train. The system definition of such a setup is presented. Several coil configurations are studied. Experimental setups for static calorimeter tests, dynamic temperature rise tests, and deicing tests are described, and results are reported. With 50-kW 185-kHz RF generator power, successful deicing was accomplished up to a speed of 43.5 km/hr at an ambient temperature of -2.2°C using a ferrite-core coil. Finally, possible future improvements to the system are discussed.

During a winter storm, snow, ice, sleet, high winds, and low temperatures often cause rail transit systems to experience a variety of equipment and operational problems. One such problem is the icing of the third rail (the rail that supplies power to trains). This causes the power collector to lose electrical contact, which results in a disabled car or creates excessive arcing. A layer of ice forms and adheres to the third rail when there is precipitation near the freezing temperature of water (0°C). Sleet storms cause the worst icing problems, but snow on the third rail that has melted in the rising daytime temperature can readily freeze if the temperature then drops below the freezing point.

Third-rail heaters have been effective in minimizing these icing problems on many transit systems. However, these ohmic heaters in general consume an inordinate amount of energy. An energy-efficient approach is to melt a thin layer of ice at the interface between the rail and the ice. This will break the strong adhesive bond between the rail and the ice layer. Once this bond has been broken, the rest of the unmelted ice can be easily removed by a mechanical scraper. Blackburn and St. John estimate the required interface melt thickness to be about 2 μm (1). The most desired mechanism for this approach would be to couple energy directly to an ice layer approximately 2 μm thick next to the interface between the rail and the ice with little or no energy being directly coupled to either the layer of ice more than 2 μm from the interface or the rail underneath. Unfortunately, this calls for a dramatic change in the physical properties of ice at the interface.

Even though there is some evidence that the ice properties are different at the interface compared with the bulk, such drastic differences are not anticipated. Hence, the next best solution is to have the energy source at the interface but located in the rail. The ice layer in immediate contact with the rail surface will be melted by the heat energy transferred from the rail to the ice. It is possible to achieve this rather easily by radio-frequency (RF) induction heating.

The basic concept of RF induction heating is rather straightforward (2,3). Essentially, a high-frequency alternating current is passed through a work coil in the close neighborhood of a load. This induces a current in the load. Its magnitude depends on the permeability of the load and falls off from the surface to the center of the work load with a rate of decrease that is higher at higher frequencies. It is this induced current that causes the rapid heating of the load.

For rails made of high-permeability materials, RF induction deicing is efficient in several respects. First, the heat is generated within the top few micrometers from the rail surface, where it is needed, and hence little is wasted by being transferred to the ambient. Second, modern RF generators have respectable conversion efficiencies. Third, this deicing system is very responsive in that rail surface temperature changes occur rapidly. The deicing is much less effective for aluminum-clad composite rails because aluminum has a much lower permeability.

An RF deicing system for third rails without coverboards, such as those used in the Boston and Chicago transit properties, is discussed. Important system design criteria are provided and discussed. The experimental setups used to test the performance of the RF system are described. Three kinds of work coils are described along with their performance testing. Finally, preliminary deicing experiment results are reported and the feasibility of a practical RF third-rail deicing system is discussed.

SYSTEM DEFINITION

To test the concept of RF deicing of the third rail, an experimental deicing system was developed. It is shown schematically in Figure 1 and consists of an RF generator, an air-core stepdown transformer, an RF work coil, and a mechanical scraper (not shown in the figure). The generator supplies RF power to the coil, which couples part of the energy to the third rail through an air gap. Flexible water-cooled lines are used to connect the generator to the transformer primary. A rigid water- or glycol-cooled transmission line is used between the transformer and the work coil for higher efficiency.

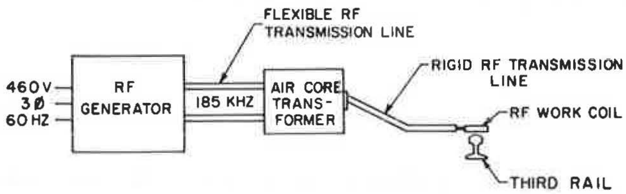

FIGURE 1 Basic components of RF deicing system.

Practical RF deicing systems would be mounted on a train. The initial goal was to develop a system with an operating speed of 24 km/hr or higher at -4°C on the uncovered third rail of the Boston transit property (the 85-lb/yd ASCE rail). A work coil lateral positioning tolerance of +5 cm and a coil-to-rail gap of 0.3 to 1.3 cm were chosen to include the effect of train vibration. To determine the system frequency and power level required for operation at 24 km/hr, a thermal analysis was conducted using a one-dimensional finite-element heat transfer model. From the results obtained, it was found that a total rail dissipation of 18 kW over a length of 30 cm was required to melt 1 μm of ice at the rail-ice interface. The operating frequency was chosen to be between 150 and 450 kHz. With this frequency range, the power absorbed in the rail is concentrated in the top several micrometers and very little energy is wasted in heating the bulk of the rail. In order to supply 18 kW to the third rail, a 50-kW RF generator was used. The power coupled to the rail depends on the work coil design, the coil-rail air gap, the lateral displacement, and the skew angle of the coil with respect to the rail. Experiments were performed to assess the deicing performance capability of various coil configurations and to measure performance parameters for each coil. Deicing experiments were then performed using all the coils. The experiments are described in the next section.

RF RAIL HEATING EXPERIMENTS

Three coil configurations were considered: the pie-wound coil, the wide reverse pie coil, and the ferrite-core coil. The first two are called air-core coils because the magnetic path through the coil is totally through air. They are 35.6 cm long, made of four turns of 1/4-in. copper tubing, and can be enclosed in fiberglass for weather protection (Figures 2 and 3). The ferrite-core coil is shown in Figure 4. It consists of a U-shaped manganese ferrite core and two four-turn coils wound on it. The specific core material was MN60 manufactured by Ceramic Magnetics, Inc., of Fairfield, New Jersey. Element testing was performed with these coils. The tests performed were the same for each coil and included the following:

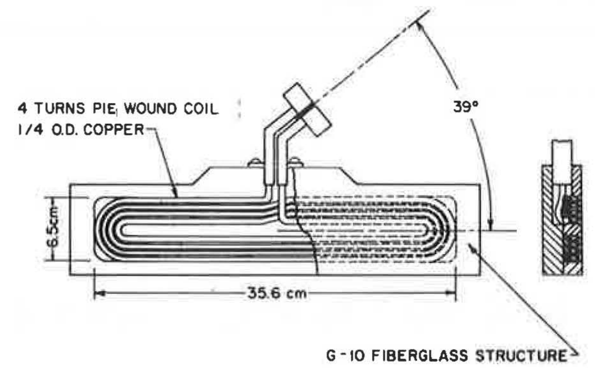

FIGURE 2 Pie-wound air-core coil.

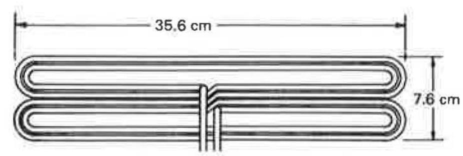

FIGURE 3 Reverse pie air-core coil.

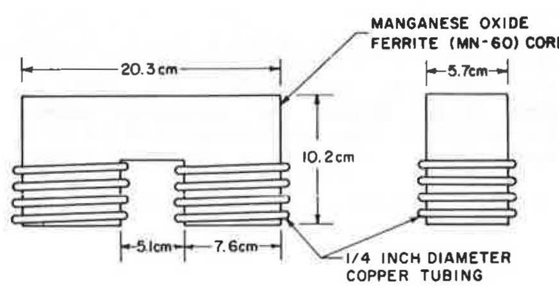

FIGURE 4 Ferrite-core coil.

1. Static calorimeter test,
2. Dynamic temperature rise tests [scanning infrared thermal imaging (Thermovision) and thermocouples], and
3. Deicing test.

The objective of the calorimeter test was to measure the net power supplied by the RF coil to the rail cap as a function of gap, skew angle, and coil lateral displacement. The test was performed using the setup shown in Figure 5. The calorimeter shown was fabricated from the cap of an 85-lb/yd ASCE rail and thus accurately simulated the actual rail. The

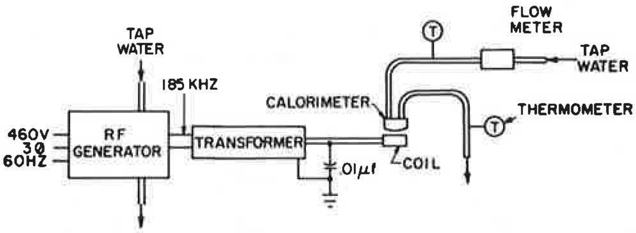

FIGURE 5 Calorimeter test setup.

water flow rate was measured using a flow meter. After the RF generator was turned on and the temperature of the calorimeter reached steady state, the temperature of the water before and after it flowed through the calorimeter was measured for various combinations of lateral displacement and skew angle (Figure 6). From these data the power absorbed by the calorimeter was calculated.

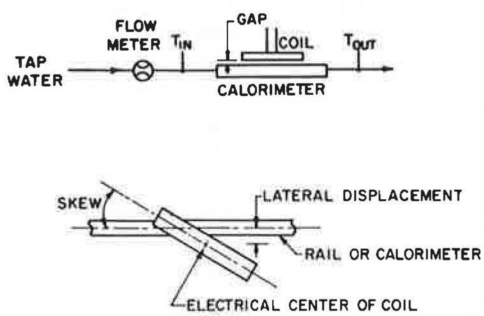

FIGURE 6 Definition of gap, skew angle, and lateral displacement.

For the most efficient deicing, the rail heating pattern must be uniform. The purpose of the surface heating profile test was to measure the surface temperature along the rail cap and to find out which coil configuration had the most uniform heating pattern. The test was conducted at room temperature with the RF work coil acting on the 85-lb/yd rail mounted on Vought Corporation's 5.8-m rotating drum. The coil-to-rail gap was set at 1.27 cm. An infrared thermal imaging system (Thermovision) and the test setup are shown in Figure 7. The view on the Thermovision monitors the heating pattern produced by the coil. To give the rail surface a high emissivity for these tests, a thin coat of flat black paint was

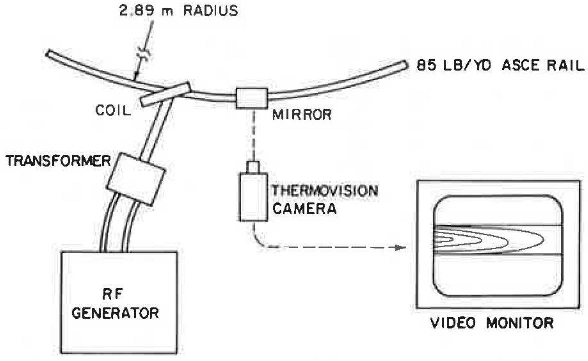

FIGURE 7 Thermovision test setup.

sprayed on the rail cap. The thickness of this coating was about 8 μm, which analysis showed would cause a negligible effect on the measured temperatures. The different temperatures on the rail cap are represented by 10 colors on the Thermovision monitor. Thermocouple measurements were then used to confirm the Thermovision response results.

In the deicing test, the actual environmental conditions were simulated. The test setup is similar to that used in the surface profile tests (Figure 8). A mechanical scraper is attached about 15 cm behind the coil. The rail was first cooled to a temperature of about -7°C and then lightly sprayed with water while it was rotated until the desired ice thickness was obtained. The ice thus formed was generally glaze ice and covered both the top and the sides of the rail cap. The rail was then allowed to stabilize to a temperature of -3.3 to -4.4°C. After stabilization, the wheel was brought up to the test speed, the generator turned on, and the scraper actuated. The deicing operation was carried out for one-fourth revolution of the drum.

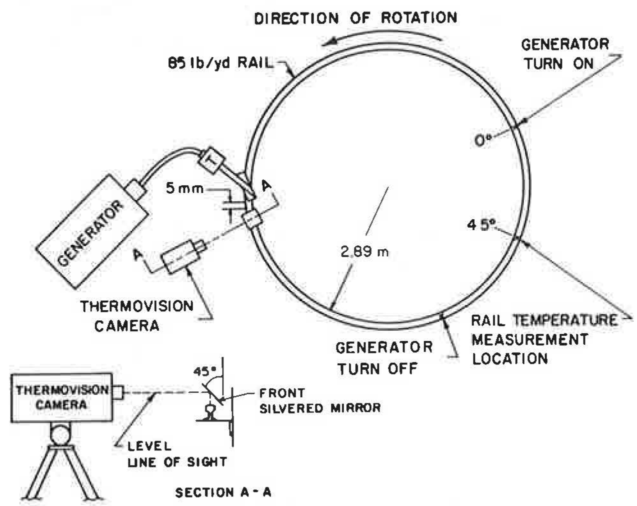

FIGURE 8 Surface heating profile experiment setup.

RESULTS AND DISCUSSION

The first coil tested with the RF system was the pie-wound air-core coil. Calorimeter test results are shown in Figure 9. As expected, the absorbed power decreases with lateral displacement. The 20-degree skew angle provides the maximum tolerance to lateral displacement. The design goal of 18 kW with up to 5-cm lateral displacement was not attained because 3.8-cm displacement was the maximum possible at 18 kW. The 20-degree skew angle was selected for the remaining tests because it provided the maximum tolerance to lateral displacement. Surface temperature profile results showed that the pie-wound coil produced nonuniform heating of the cap with highest temperature at the corners. The heating also extended around to the side of the cap where heating was not needed in the deicing operation. Deicing tests were performed for a rail temperature of about -4°C. The maximum deicing speed attainable was 8.85 km/hr for this coil.

The magnetic flux pattern for the reverse pie coil is quite different from that of the pie-wound coil. Such an arrangement would be expected to produce more uniform heating of the rail. The surface temperature rise results confirmed this. A much more

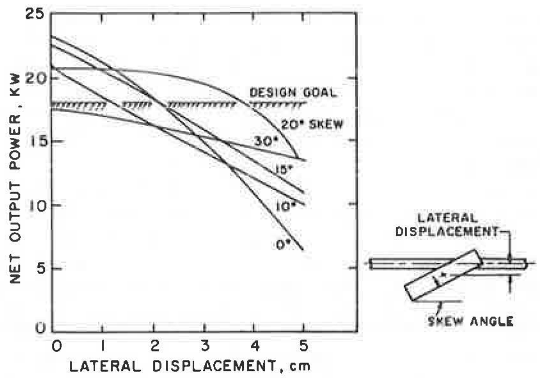

FIGURE 9 Calorimeter test results: pie-wound coil.

uniform distribution of energy to the rail cap than the pie coil was obtained. On the other hand, the calorimeter test results (Figure 10) showed that the reverse pie coil provided less lateral tolerance. A skew angle of 15 degrees is seen to provide the best compromise between power input and lateral displacement. Using the reverse pie coil, complete deicing was achieved up to 12.9 km/hr.

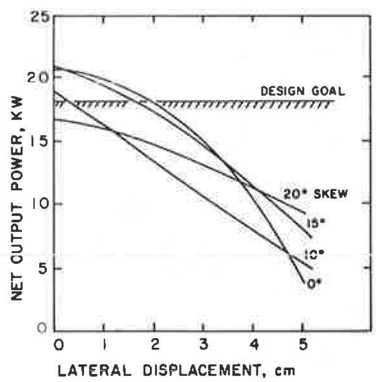

FIGURE 10 Calorimeter test results: reverse pie-wound coil.

The ferrite-core coil was designed to be used with little or no skew or lateral displacement. Calorimeter test results showed that the use of a ferrite core greatly increases the energy coupling to the rail. This was because the ferrite core provided a highly conductive path for the magnetic flux, reduced the leakage, and concentrated the flux into a smaller area in the rail cap. A maximum deicing speed of 43.5 km/hr was achieved for a rail temperature of about -2.2°C, which was the best deicing speed of all coils tested. However, in its current form, the ferrite-core coil suffers from substantial internal heating and produces the most nonuniform heating of the coils tested. This coil will require additional development. Laminating the core material can limit internal heating and an alternative core configuration will help to achieve a more uniform heating and thus increase the deicing speed.

CONCLUSION

Experimental results have shown that a practical third-rail deicing system using RF energy is feasible. However, many problems still need to be solved for development of a practical system. Based on this work, further research and development in the following areas is recommended:

1. Work-coil coupling efficiency and rail cap heating uniformity need to be increased. This can be accomplished by improving the design of the coil.
2. The provision for automatic matching of the load impedance to the RF generator is needed. This will ensure constant power to the rail while the train is moving.
3. The problem of RF generator cooling has not yet been addressed. A closed-circuit water-cooling system needs to be installed on the train and the coolant must not freeze in winter.
4. In the absence of ice and at a slow vehicle speed, efficient RF coupling results in rapid rail surface heating and oxidation. Some feedback control mechanism is thus needed for rail overheat protection.
5. The 200-kHz 50-kW RF generator used in the foregoing experiments has a vacuum tube oscillator. The generator is rather bulky and its ruggedness has not been tested. One possible solution is to replace it with a solid-state RF generator (50 kHz), which is smaller, lighter, and less costly. Another important feature of the solid-state generator is that its primary power can be 600 V dc, which can be tapped directly from the third rail. A thermal analysis will be needed to determine the effect of the lower frequency on the deicing efficiency.
6. The effects of the electromagnetic radiation from the RF generator must be studied. The possibility of electromagnetic interference with vehicle control and communication must be investigated. The biological effects of any possible radiation leakage should also be addressed.
7. Other engineering developments needed include a tracking mechanism for the RF work coil to follow the rail, a flexible transmission line between the transformer and the coil, and weather protection for the air-core transformer.

Even though the results reported in this paper were based on the uncovered third rails, the system can be modified for third rails having coverboards. The air-core coils described in this paper are small enough to fit between the third rail and the coverboard, but the mechanical scraper must be specially designed. The rest of the system would be housed inside a vehicle and thus does not require any extensive modification.

With all the foregoing developments incorporated, the RF deicing system may prove to be a good alternative solution for third-rail problems in adverse weather.

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Morning Peak Hours in the Stuttgart Transit and Tariff Authority

WERNER BRÖG, ERHARD ERL, and WOLFGANG WÖRNER

ABSTRACT

The problem of traveling on public transportation during the morning peak hours is well known but has not been solved. This is because peak-hour traffic volume can only be reduced if the individuals who have the option of starting work at different times actually make use of this option. However, changing work and school schedules has an impact not only on the transport system but also on an individual's private life. The results of a study conducted by the Stuttgart Transit and Tariff Authority are described. The characteristics of public transit use in the morning peak hours are shown. The potential of transit users who have flexible schedules is indicated and a number of policies to deal with the problem are suggested. Furthermore, the potential number is determined of those who can react to the negative conditions of public transit in peak hours by switching to other modes of transportation.

The focus of specialist discussions geared at finding ways to reduce peak-hour travel is to extend the times when work and school begin (1) over a longer period of time. The effectiveness of policies that might accomplish such a change has repeatedly been proven theoretically but the problem has not been solved. This is because peak-hour traffic volume can only be reduced if the individuals who have the option of starting work at different times actually make use of this option. However, changing work and school schedules has an impact not only on the transport system but also on an individual's private life. Accustomed daily routines are interfered with and usual social contacts are hampered (2).

The Stuttgart Transit and Tariff Authority (VVS) commissioned a team of social scientists to conduct a study (3) in order to get information on the problem of peak-hour travel in a specific area and on the impact that different policies would have on the problem of peak-hour travel. VVS wanted special attention paid to the social situation of public transit passengers.

VVS serves an area of 3012 km^2 (about 1,145 $miles^2$) with a population of 2.14 million. In 1979, 655,000 passenger trips per weekday were made by buses, streetcars, and S-bahn (rail rapid transit) in the system (4). About 13 percent of these trips are peak-hour trips in the definition of this study (incoming traffic to the central zone of the service area between 6:00 and 8:00 a.m.). During the morning peak hours, public transit is used to the limit of its capacity.

The study of peak-hour traffic was done in two stages. From a regional travel survey (5) there was information on 67,700 persons and 51,900 public transit trips. These data were used for a descriptive evaluation of peak-hour travel. They also gave the base for in-depth interviews with a subsample of 316 households in which peak-hour passengers lived. The results of these interviews are presented in this paper.

FLEXIBILITY OF PEAK-HOUR PASSENGERS

The analysis is based on those trips recorded in the travel survey that are defined as peak-hour trips. For these trips, it must be determined whether and under what conditions flexibility in scheduling is possible.

To make temporal flexibility operational, a 30-min adjustment in the beginning time of trips is used in accordance with the literature on the subject (6). An interviewee is said to be flexible in scheduling his time if he can organize his daily routine so that the peak-hour trips can be made either 0.5 hr earlier or later.

For the situational analysis, all of the characteristics explored in the interview that pertain to the individual and the trip and that are of explanatory value in the given instance are used. Thus, it is necessary to divide the temporal variability into individual dimensions to which the characteristics determining the situation can be assigned (see Figure 1).