Radio Frequency Deicing of Collector Rails for AGT Systems

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Radio frequency (RF) induction heating has been proposed as an alternative deicing technique for automatic guideway transit (AGT) collector rails under adverse weather conditions. The concepts of a practical RF deicing system are discussed. A working frequency of 450 kHz is used for the RF generator, and 430 magnetic stainless steel is selected as the rail-capping material for efficient coupling. Experimental setup for a model RF deicing system is described. With 2.5-kW RF generator power, successful deicing was accomplished up to a rail speed of 3.2 km/h for rail temperatures as low as -30°C. The performance of this test system is assessed, and possible future improvements are suggested.

In recent years, many automatic guideway transit (AGT) systems have been developed. These systems are designed to transport people and cargo over short distances safely and automatically. In general, they all employ sophisticated computers and other electronic equipment to provide operational efficiency and flexibility. Under normal weather conditions they are very reliable. However, frequent shutdown does occur during periods of severe cold weather. One of the main reasons for system failure is the interruption of power and signal communications due to frost and ice formation on the collector and conductor rails. Icing of power and/or signal rails occurs frequently and often before the loss of traction due to winter weather.

Various snow- and ice-control methods have been adopted or suggested (1). Most of the feasible approaches fall into one of the following categories:

1. Rail heating,
2. Covered rails,
3. Mechanical scraping,
4. Spraying with chemicals,
5. Modified collector brush and modified rail, and
6. Inductive control (contactless pickup).

The last method--inductive control--has been used in several systems (1) and has proved to be quite successful in minimizing the effect of ice on signal communication. For systems that use direct physical contact for signal pickup, other methods in the above list are more appropriate. One method that has had limited success is direct rail heating. Rail heating, which uses electrical resistance elements, was tried in several AGT systems (1-4). Other deicing techniques that use advanced technologies such as lasers, microwaves, or ultrasonics have been suggested, and some research is under way (5) to investigate their effectiveness.

In this paper, a novel deicing concept that uses an old, well-known phenomenon in electrical engineering is described. The basic idea is to heat the top surface of the collector rail with radio frequency (RF) energy, which creates a thin layer of water at the interface between the ice and the rail. The loosened ice can then be easily scraped away with a mechanical scraper. RF induction heating is efficient in several respects. First, the heat is generated within the top few micrometers from the rail surface right 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 rather rapidly. There are other advantages that will be discussed later in the paper. With proper choice of frequency, rail material, and work coil design, effective rail deicing at moderate vehicle speeds and subzero ambient temperature is possible with input power as low as a few kilowatts.

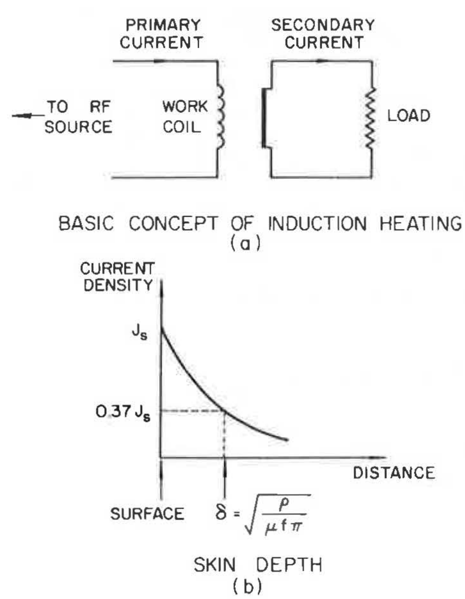
This paper reviews the basic theory of RF heating and presents the RF collector rail deicing system concepts. Important designing criteria are provided and discussed. Deicing experiment results that use a prototype RF system are reported. Finally, areas for future system improvements are suggested.

BASIC THEORY OF RF INDUCTION HEATING

Induction heating is based on three main principles: electromagnetic induction, "skin effect", and heat transfer. The basic concept of induction can be shown to be similar to the well-known transformer theory. An alternating current is passed through the primary coil (called the work coil) in the neighborhood of the work load, which can be considered to be a single-turn, short-circuited secondary winding (Figure 1a). The current in the work coil develops a magnetic field that induces an electric current in the secondary circuit. Because of the high turn ratio, the current (I) induced in the secondary circuit will be high and considerable loss in the form of I^2R heating will develop in the load, thus raising its temperature.

In magnetic materials, there is another form of loss called the hysteresis loss, which may also contribute to the heating. The induced current falls off from the surface to the center of the work load, and the rate of decrease is higher at higher frequencies. The rate is also dependent on two proper-

Figure 1. Basic concept of induction heating and skin depth.



ties of the material, namely, the resistivity (ρ) and the relative permeability (μ). The term skin depth is the depth where the current density has fallen to 0.368 (1/e) of its surface value (Figure 1b). The skin depth (δ) is related to frequency and material properties by the following equation:

$$\delta = \sqrt{\rho/\mu f \pi} \qquad (1)$$

At high frequencies, the skin depth will be small and the induced current will concentrate near the surface, which results in rapid surface heating. Of course, part of the heat generated will be conducted into the rail away from the surface, thereby reducing surface heating. For optimal performance, therefore, some form of insulation may be helpful. This will be discussed in more detail later.

The skin depth for primary current (current in the work coil) is also small at high frequencies and some heating results in the work coil, which must thus be water cooled. Because the main objective is to maximize the heat in the load, coil losses must be kept to a minimum, i.e., the coil must be designed for maximum efficiency. The coil efficiency (η) is defined as

$$\eta = P_{work}/(P_{work} + P_{coil}) \qquad (2)$$

where P_{work} is the power loss in the work load and P_{coil} is the power loss in the coil.

An approximate expression for the idealized coil efficiency relation can be written as follows:

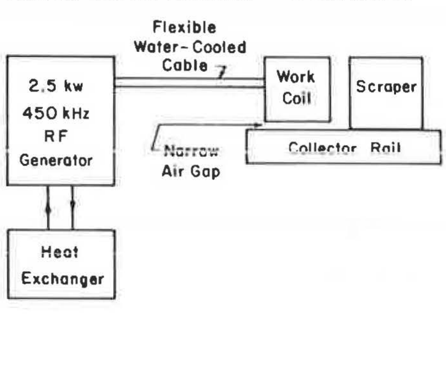
$$\eta \cong 1/(1 + \sqrt{\rho_c\, \mu_c/\rho_w\, \mu_w}) \qquad (3)$$

where ρ_c and ρ_w are the resistivities for the work coil and the load, respectively, and μ_c and μ_w are the relative permeabilities for the work coil and the load, respectively (6). Thus, for best efficiency, the work coil should be made of silver-plated copper, which has a low ρ_c and a unity μ_c. In addition, the work load should be made of a high resistivity and permeability material such as steel. A more detailed account of the choice of coil and rail materials is given in the next section.

RF DEICING-SYSTEM CONCEPTS

The basic RF deicing system is shown in Figure 2. It consists of an RF generator, a flexible RF power cable, a work coil, a mechanical scraping attachment, and a heat exchanger. For the generator, the major decision criteria are frequency and power level. A reliable deicing system should work in severe weather conditions with ambient temperatures as low as -30°C. Under these conditions, ice may form from atmospheric precipitation, wet splashes, or even moisture in the air. To completely melt the ice layer becomes increasingly expensive as the thickness of ice is increased and the temperature is decreased. Even at moderate speed, an enormous amount of energy is needed to raise the temperature of the ice from a subzero temperature to freezing point to supply the necessary latent heat of fusion for melting and to compensate the heat lost through conduction and convection. At 56.4 km/h, for example, just for the melting process alone, approximately 200 kW of power must be supplied to a 0.32-cm-thick layer of ice atop a typical signal rail. It is beyond any doubt that completely melting the ice on the rail is not a cost-effective approach.

Figure 2. Basic components of RF deicing system.



An ideal solution will be to melt a thin layer of ice at the rail and ice interface, thus breaking the ice-rail bond. The rest of the ice is then removed by a subsequent scraping operation. Because of the nature of RF heating, this ideal situation can largely be achieved. By choosing a relatively high frequency, i.e., a frequency between 10 kHz and 1 MHz, the skin depth can be made very small. As a result, most of the energy is dissipated in the top thin layer of the rail next to the ice, which results in rapid heating and melting of the interface ice layer. Because the heat is very much localized and is generated where it is most needed, the RF deicing system is inherently efficient.

Initial estimates show that an RF generator with output power less than 10 kW should be adequate for typical AGT rail deicing. Moreover, the conversion efficiency for the RF generator itself is very high; thus, the overall system efficiency [from the alternating current (AC) power line to heat in the rail] should be quite respectable. As mentioned earlier, this efficiency is very much dependent on coil design and rail material. The coil-load coupling efficiency is of critical importance in the overall system performance. This point will be addressed further later.

Modern RF generators use solid-state silicon-controlled rectifiers (SCRs) as the rectifying elements. Hence, these generators are compact, rugged, and reliable and are suitable to be vehicle mounted. However, the oscillator tube of the generator and the work coil itself must be water cooled. The deicing system thus requires a closed-circuit water circulation system--namely, a heat exchanger. The RF power from the generator is delivered to the work coil via a flexible water-cooled coaxial cable specially designed for the best power transfer.

EXPERIMENTAL SETUP

Experiments were designed to test the feasibility of the RF deicing technique and to establish guidelines for future prototype designs of an AGT RF deicing system. Figure 3 is a sketch of the experimental setup. The RF power from the Lepel 2.5-kW, 450-kHz generator is fed via a water-cooled coaxial cable (made by L.C. Miller Company) to the work coil, which is enclosed in an environmental chamber. The coil is of a multiple-turn pancake shape, which is designed to deliver energy efficiently into the rail and at the same time to ride freely over the rail surface.

A square-shaped copper tube is employed in the construction of the coil (Figure 4). Because the distance between the coil and the rail must be small for high energy transfer efficiency, the coil is coated with epoxy to prevent spark-over caused by the water on the rail. In order to simulate the relative motion of the coil with respect to the rail, the latter is pulled by a motor through a pulley system. The maximum speed attainable for this setup is about 3.2 km/h. As was discussed earlier, the best coil efficiency is obtained with a work piece made of high-resistivity and high-permeability material.

Our test rail is a modified version of the new rails designed to be used in Vought Corporation's Airtrans system installed at the Dallas/Fort Worth Airport. It is made of stainless-steel-clad aluminum (Figure 5). Such a rail has many advantages over the old copper-clad steel-rail system used earlier, especially in the RF deicing application.

For the Airtrans system, 304 nonmagnetic stainless steel has recently been used to replace the old copper-clad rail. For our experiment, 430 magnetic stainless steel is used. Except for the magnetic properties, this steel is roughly similar to the 304 steel in corrosion resistance, strength, and other mechanical properties (7). Like the 304 stainless steel, the 430 steel is also a general-purpose type and is easily available.

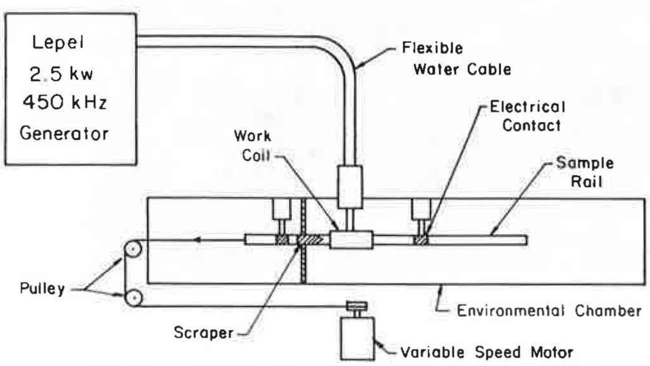
Sample rails (with cross section shown in Figure 5) were made. Deicing experiments were performed by using the 430 steel-clad rails. A rail with a 304 stainless-steel cap was also used for the purpose of comparison. Because steel is a relatively good thermal conductor, some of the heat generated near the surface of the rail is conducted to the bulk of the rail, which decreases the overall deicing efficiency.

It is estimated that some form of insulation beneath the stainless-steel cap may slow the conduction process and help to increase efficiency (8). Hence, two modified sample rails were made, one with a hollow cavity beneath the cap and the other with asbestos insulation (Figure 6). These rails were used in our experiments to determine the effectiveness of insulation.

For some experiments, the ambient temperature around the rail must be maintained at a constant subzero point. This is accomplished inside the environmental chamber, which is a long wooden box insulated with thick styrofoam and cooled by a stream of cold air.

In the Vought Corporation's AGT system, the signal is picked up with a graphite collector shoe that is physically in touch with the rail. Signal transfer fails when the intimacy of contact is broken by a layer of ice. Two small pick-up contacts made of the same variety of graphite are used in our experiment to measure the contact resistance before and after RF deicing. A small light bulb is connected in series with each pick-up contact and the rail. A good electrical contact will be indicated by a lighted bulb. Finally, a mechanical scraper is installed about 5.1 cm away from the work coil. At very low rail speeds, when using our work coil, 2.5 kW of RF power is sufficient to completely melt approximately 0.32 cm of ice. The scraper becomes useful when the rail is moving at higher speeds. A more detailed account of the function of the scraper is given in the next section.

Figure 3. Experimental setup for RF deicing system.

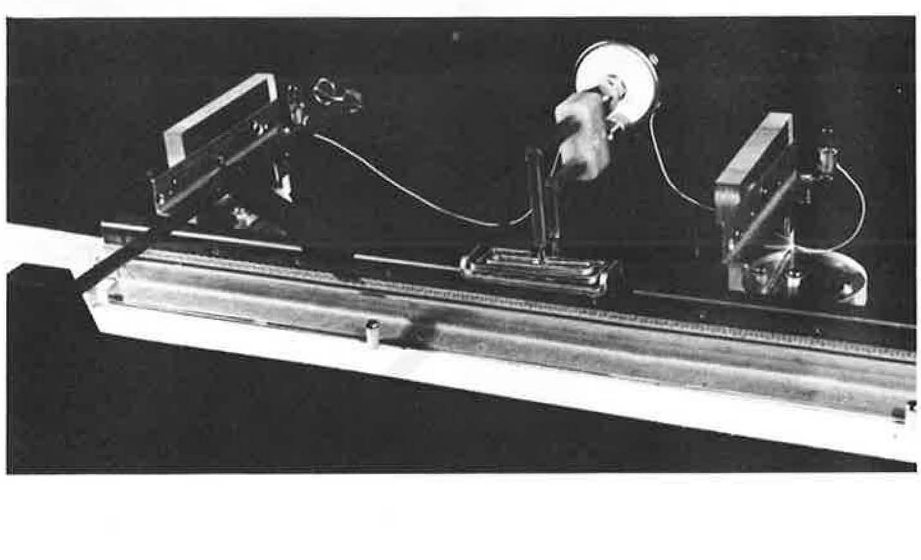


RESULTS AND DISCUSSIONS

The 430 stainless-steel-clad sample rails used in the experiments were each 1 m long. The surface of the rail under test was first carefully cleaned and degreased to ensure good ice adhesion. It was initially cooled down to -10°C in a dry-ice box. Water was then sprayed onto its surface and a thin layer of ice gradually built up until its thickness reached about 0.32 cm. This ice layer was strong and without cracks. The ice-covered rail was further cooled down to dry-ice temperature (~ -56°C) before it was quickly transferred to the environmental chamber for testing. For the duration of the experiment, the chamber was kept at -10°C and the rail temperature was approximately -35°C.

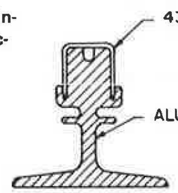
The distance between the work coil and the rail surface was set at 0.63 cm. The RF power output from the generator was tuned to its maximum, and the ice-covered rail was pulled through below the work coil at various speeds, ranging from less than 0.81 to 3.2 km/h. At lower speeds, the power coupled to the rail was enough to completely melt the ice layer. Under this condition, the portion of the rail, after passing through the work coil, made good electrical connections to the aft-contact as evidenced by the lit-up test bulb. Generally, because of the cold environment, the water film on the rail surface refroze within a few seconds. A solution to this is to remove the water by using a jet of warm compressed air, which will be discussed later.

Figure 4. Relative positions of work coil, scraper, and contacts inside environmental chamber.



At speeds around 3.2 km/h, complete melting of the ice layer no longer occurred. Instead, a water film was formed at the ice-rail interface. The ice layer now loosened from the rail surface was immediately removed by the scraper (Figure 7). Even though a speed of 3.2 km/h is rather slow, this result is considered to be encouraging because our prototype work coil is still not of the optimal design. Moreover, the experiments were performed for a rail temperature of -35°C, a situation rarely encountered. For higher temperature ranges and with further improvements in coil design, satisfactory deicing should be possible at higher vehicle speeds. Because of the limitation of our linear-motion testing setup, deicing experiments with higher rail speeds have not been carried out. However, a 5.5-m-diameter rotating drum test facility at the Vought Corporation is now being modified for future high-speed testing (9).

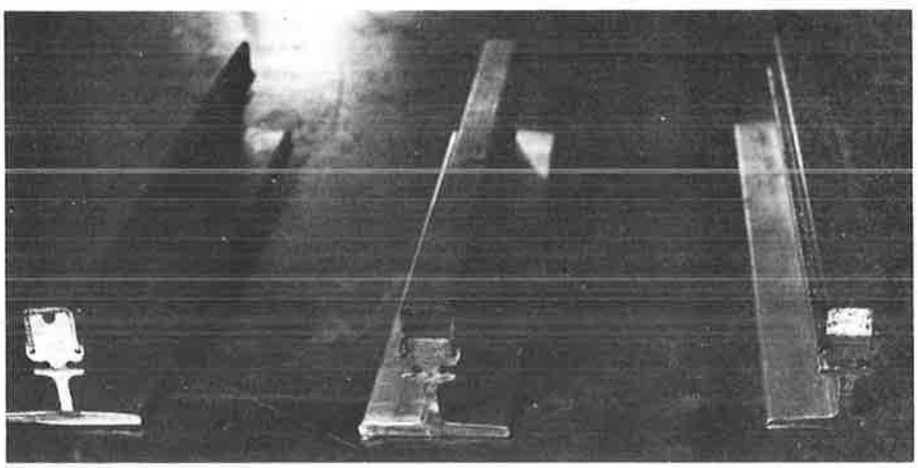
Figure 5. Cross section of stainless-steel-clad aluminum collector rail.



The power coupled to the rail was estimated by measuring the generator plate voltage (V_p), the plate current (I_{po}) under no load (no rail under coil), and the plate current (I_p) under load (with rail under coil). V_pI_{po} gives the power dissipated in the work coil and $V_pI_p - V_pI_{po}$ is the power coupled to the load. The results are given in Table 1. It is seen that, for our prototype coil, only about 0.58 kW is coupled to the rail, which results in a coupling efficiency of only 19 percent for the 430 stainless-steel rails. As expected, the efficiency for 304 stainless-steel rails is much lower. The data also show that the coupling efficiency can be increased if the air gap between the coil and the rail can be reduced. Because a reduction of gap to less than 0.63 cm is not practical, the development of a more efficient coil becomes the only choice for improving system performance.

The evaluation of the performance for insulated rails was carried out in the following manner. Some 40-60 tin-lead solder with a melting point of 183°C was cut into small pieces of equal sizes. One piece

Figure 6. Sample rails for insulation effectiveness experiment: (a) control rail, (b) hollow rail, and (c) asbestos-insulated rail.



a b c

Figure 7. Actual deicing in progress with rail moving at 3.2 km/h.

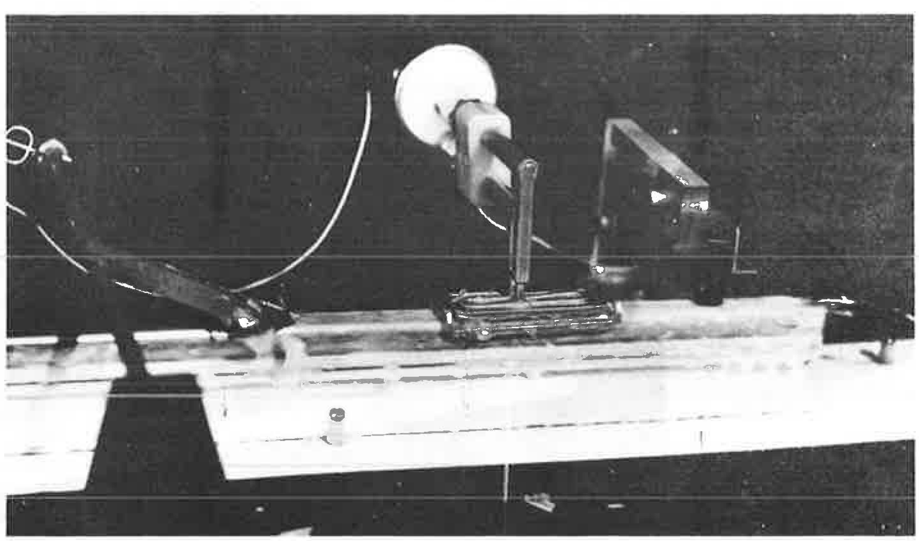


Table 1. Data for calculating coil coupling efficiency.

Load Condition	Plate Voltage (V_p) (A)	Plate Current (I_p) (A)	$P_{coil} + P_{work}$ (V_pI_p) (kW)	P_{work} (kW)	η (%)
No load	4350	0.55	2.4	0	
Air gap between work coil and rail = 0.63 cm					
430 rail	4250	0.70	2.98	0.58	19
304 rail	4325	0.58	2.51	0.11	4.4
430 rail plus ice	4250	0.70	2.98	0.58	19
Air gap between work coil and rail = 0.32 cm					
430 rail	4250	0.75	3.19	0.79	25
304 rail	4250	0.61	2.59	0.19	7.3

Table 2. Time taken for small flat piece of 40-60 solder to melt on RF-heated rails.

Sample Rail	Plate Current (A)	Time to Melt (s)
304 SS standard	0.63	12.2
304 SS hollow	0.63	8.2
304 SS asbestos	0.63	7.9
430 SS standard	0.75	2.4
430 SS hollow	0.75	2.1

Note: Distance between work coil and rail surface = 0.25 cm.

was flattened on each of the following rail samples: 304 stainless-steel (SS) standard rail, 304 SS rail with a hollow section beneath, 304 SS rail with asbestos insulation (as shown in Figure 6) along with 430 SS standard rail, and 430 SS rail with a hollow section.

Each of these sample rails with solder on it was in turn placed under the RF coil with a coil-rail clearance of 0.25 cm. The exact time required for the solder to melt was recorded. The results are given in Table 2. The following three pertinent observations are made from the data given in this table:

1. As we already know, the 304 SS rail heats up at a much slower rate than the 430 SS rail;
2. Because of the long time required for 304 SS rails to heat up, thermal insulation becomes an important factor; and
3. Little improvement on the heating efficiency is obtained by thermally insulating the 430 SS rails.

Because thermal conduction is a rather slow process, the advantages gained from insulating the rail depend on the power density coupled to the rail. In the case of the 430 SS rails, the coupled power density is higher, and hence only a smaller fraction of thermal energy is conducted away before the solder melts as compared with the 304 SS rails. This can be further seen by comparing data from Tables 1 and 2. From Table 1, for an air gap of 0.32 cm, the ratio of coupled power efficiency between the 430 SS and the 304 SS rails is about 3.4. From Table 2, for a 0.25-cm air gap, the ratio of time necessary to heat the surface to 183°C for 304 SS rail to that necessary for 430 SS rail is 5 for the standard rail configuration and 3.9 for the hollow configuration. Clearly, the lower coupled power efficiency in 304 SS implies a larger amount of thermal losses for attaining the same surface rail temperature and, in such cases, the insulation does play an important role. However, when the coupled power density is high, the insulation does not substantially affect the heating of the surface rail, as evident from Table 2 data on 403 SS rail samples. Hence, in such cases, for the initial deicing cycle, insulation is not necessary. However, good insulation will certainly slow down the refreezing of water on the rail surface. Whether or not rail insulation plays an important role in overall system performance will depend on the actual engineering design of the deicing head (coil, scraper, electrical contacts), the coupled power density, and the speed of motion. In our opinion, the effectiveness of thermal insulation needs to be studied further.

In passing, it must be noted that the use of insulated rails poses no current-carrying capability problem for the signal rail, which carries a small amount of current. However, since large currents (up to 350 A) flow in the power rails, the insulation cavity, if used, must be appropriately designed and care taken to maintain a sufficiently large contact area between the stainless-steel cap and the aluminum base to allow a low resistance path for current flow.

ENERGY CONSUMPTION FOR RF DEICING

Many of the existing AGT systems, such as in Morgantown, West Virginia, employ electric rail heating to combat snow and ice problems (3). It is of interest to estimate the energy consumption of RF heating and compare it with that of resistive heating. Energy consumption depends on many factors such as climate, guideway length, operating hours, rail design, etc. For analysis purpose, a baseline AGT system is assumed. Its characteristics are given in the table below:

Item	Value
No. of cars during operating hours	
7:00-9:00 a.m.	18
9:00 a.m.-5:00 p.m.	4
5:00-7:00 p.m.	18
7:00-11:00 p.m.	2
Guideway length (km)	10
No. of rails	4
No. of vehicles	20
No. of heating hours per year	250

From the table, it is seen that the average number of cars operating each hour is 7. We estimate that 5-kW RF power will be sufficient to deice one rail under most winter conditions. Thus, 20 kW is needed for each vehcle. The total annual energy consumption by using RF heating is as follows

$$7 \text{ cars} \times 20 \text{ (kW/car)} \times 250 \text{ h} = 3.5 \times 10^4 \text{ kW-h} \tag{4}$$

On the other hand, for resistive heating, the power input to the rail depends on many factors, such as temperature, wind speed, shape of rail, etc. A power requirement as high as 98 W/m per rail is sometimes necessary (9). However, for moderately cold weather, the average power requirement is about 49 W/m per rail (4). For a 10-km guideway with a four-rail collector system, the annual energy consumption is as follows:

$$4 \times 49 \text{ (W/m)} \times 10 \text{ km} \times 250 \text{ h} = 4.9 \times 10^5 \text{ kW-h} \tag{5}$$

On a per-rail basis, resistive heating energy consumption is about 1.2×10^5 kW-h/rail/year. RF heating consumes about 0.88×10^4 kW-h/rail/year, which is about 7 percent of that for resistive heating for the baseline AGT system under consideration here.

It is important to note here that the energy requirement for the direct electrical rail heating system is independent of the frequency of operating cars, while that of the RF inductive heating system is not. In the latter system, the energy requirement is proportional to the frequency of operating vehicles. This implies considerably less energy consumption during the nonrush hours when fewer cars are operating. As a result, such a system shows promise for an energy-efficient solution to the problems.

CONCLUSIONS

RF induction deicing appears to be a promising alternative to the direct electric rail heating method. RF deicing systems can be attached to future AGT vehicles for adverse weather rail deicing operation. The prototype system built in our laboratory has successfully demonstrated the concept of RF rail deicing. Based on this work, we recommend further research and development work in the following areas:

1. Work coil coupling efficiency needs to be increased. This can be accomplished by improving the design of the coil. Using silver-plated copper tubings and including a ferrite concentrator for the work coil will also improve performance.
2. A provision for automatic matching of the load impedance to the RF generator is needed.
3. The possibility of using frequencies other than the 450 kHz used in this work should also be investigated with improvements in overall system efficiency in mind along with other considerations such as cost, compactness, and ruggedness.
4. A more effective mechanical scraper design is also needed. A nozzle for warm compressed air installed right next to the scraper will be useful in blowing and drying the thin layer of water on the rail surface, thereby avoiding the refreezing problem. The heat exchanger necessary for the RF generator can supply part or all of the energy necessary to warm the compressed air jet.
5. 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.

With all the above improvements incorporated, the RF deicing system may prove to be a good alternative solution to AGT adverse weather problems.

ACKNOWLEDGMENT

This work has been supported by the Urban Mass Transportation Administration, U.S. Department of Transportation, under a contract for the Cold Weather Transit Technology Program.

We would like to express our appreciation to Walter Gajda and David Randolph for their valuable suggestions and advice. Thanks also are extended to Michael Larkin of the University of Notre Dame and Rick Hicks of the Vought Corporation for their assistance in the experimental work.

REFERENCES

1. R.J. Patton and R.R. Raven. Combatting Ice on Airtrans and Other Guideways. In Snow Removal and Ice Control Research, TRB, Special Rept. 185, 1979, pp. 328-336.
2. R.D. Stevens and T.J. Nicarico. All-Weather Protection for AGT Guideways and Stations. In Snow Removal and Ice Control Research, TRB, Special Rept. 185, 1979, pp. 337-342.
3. DeLeuw, Cather and Company; ABAM Engineers, Inc. Weather Protection Review. In AGT Guideway and Station Technology, UMTA, Rept. UMTA-IT-06-0152-79-1, Vol. 2, 1978.
4. DeLeuw, Cather and Company; ABAM Engineers, Inc. Weather Protection Concepts. In AGT Guideway and Station Technology, UMTA, Rept. UMTA-IT-06-0152-79-7, Vol. 8, 1979.
5. Cold Weather Transit Technology Program, Final Report. College of Engineering, Univ. of Notre Dame, Notre Dame, IN, 1981.
6. J. Davies and P. Simpson. Induction Heating Handbook. McGraw-Hill, New York, 1979.
7. Metals Handbook, 8th ed. American Society for Metals, Metals Park, OH, Vol. 1, 1978.
8. Cold Weather Transit Technology. College of Engineering, Univ. of Notre Dame, Notre Dame, IN, Quarterly Rept., Sept. 1980.
9. Airtrans Urban Technology Program, Phase II. U.S. Department of Transportation, Rept. UMTA-TX-06-0020-79-7, Vol. 6, 1979.

Publication of this paper sponsored by Committee on New Transportation Systems and Technology.