WL-TR-94-3058

APPLICATION OF MICROWAVE ENERGY FOR DISBONDING ICE FROM RUNWAYS

DR R.N. LOTHES
J.A. MONSON
D.J. O'SHEA

RESEARCH ASSOCIATES OF SYRACUSE, INC
HANCOCK ARMY COMPLEX
510 STEWART DRIVE
N. SYRACUSE NY 13212

NOVEMBER 1993

FINAL REPORT FOR 10/01/92-09/01/93

FLIGHT DYNAMICS DIRECTORATE
WRIGHT LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT PATTERSON AFB OH 45433-7562

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely Government-related procurement, the United States Government incurs no responsibility or any obligation whatsoever. The fact that the government may have formulated or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication, or otherwise in any manner construed, as licensing the holder, or any other person or corporation; or as conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This report is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

THOMAS C. HARDY
Project Officer

THOMAS C. HARDY
Acting Chief, Air Base
Operability and Repair Section

H. EDWARD BROWN
Acting Chief
Air Base Systems Branch

If your address has changed, if you wish to be removed from our mailing list, or if the addressee is no longer employed by your organization please notify WL/FIV, WPAFB, OH 45433-7562 to help us maintain a current mailing list.

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE: NOV 1993

3. REPORT TYPE AND DATES COVERED: FINAL 10/01/92--09/01/93

4. TITLE AND SUBTITLE: APPLICATION OF MICROWAVE ENERGY FOR DISBONDING ICE FROM RUNWAYS

5. FUNDING NUMBERS
C F08635-92-C-0012
PE 62206
PR 2673
TA 41
WU 01

6. AUTHOR(S): DR R.N. LOTHES
J.A. MONSON
D.J. O'SHEA

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
RESEARCH ASSOCIATES OF SYRACUSE, INC
HANCOCK ARMY COMPLEX
510 STEWART DRIVE
N. SYRACUSE NY 13212

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
FLIGHT DYNAMICS DIRECTORATE
WRIGHT LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT PATTERSON AFB OH 45433-7562

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
WL-TR-94-3058

11. SUPPLEMENTARY NOTES PREPARED FOR:
WRIGHT LABORATORY, AIR BASE SYSTEMS BRANCH (WL/FIVC-OL)
139 BARNES DRIVE STE 2
TYNDALL AFB FL 32403-5323

12a. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED.

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*) THE PURPOSE OF THE PROGRAM WAS TO DISBOND ICE FROM RUNWAY SURFACES AS AN ALTERNATIVE TO THE USE OF CHEMICALS FOR MELTING THE ICE. THE CONCEPT DEPENDS ON MICROWAVE ENERGY TO HEAT THE RUNWAY SURFACE SUFFICIENTLY TO CREATE A THIN MELT ZONE AT THE ICE PAVEMENT INTERFACE THEREBY DISRUPTING THE BOND THAT MAKES MECHANICAL CLEARING OF ICE SO DIFFICULT. COMPLETE MELTING OF AN ICE LAYER, EVEN IF ONLY A FEW MILLIMETERS THICK, WOULD BE PROHIBITIVELY EXPENSIVE. THE HOPE WAS THAT DISBONDING COULD BE ACCOMPLISHED BY MELTING SUCH A THIN LAYER THAT THE MICROWAVE TECHNIQUE WOULD PROVE AFFORDABLE, AND THAT THE COST WOULD BE OFFSET BY AVOIDANCE OF THE DELETERIOUS EFFECTS OF CHEMICAL MELTING.

14. SUBJECT TERMS
DEICING RUNWAYS, MICROWAVE DEICER, ICE DISBONDING
RUNWAY ICE MELTING, RUNWAY CLEARING

15. NUMBER OF PAGES 45

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

List of Figures

List of Tables

EXECUTIVE SUMMARY

This is a summary of the work carried out by Research Associates of Syracuse (RAS) under contract No. F08635-92-C-0012 for the U.S. Air Force. The Air Force Project Engineer was Mr. Tom Hardy, Headquarters, AFCESA/RACO, Tyndall AFB, FL 32403-6001. The RAS program manager was Mr. John Monson. The purpose of the program was to investigate the feasibility of applying microwave energy to disbond ice from runway surfaces as an alternative to the use of chemicals for melting the ice. The concept depends on microwave energy to heat the runway surface sufficiently to create a thin melt zone at the ice-pavement interface, thereby disrupting the bond that makes mechanical clearing of ice so difficult. Complete melting of an ice layer, even if only a few millimeters thick, would be prohibitively expensive. The hope was that disbonding could be accomplished by melting such a thin layer that the microwave technique would prove affordable, and that the cost would be offset by avoidance of the deleterious effects of chemical melting.

Ice is essentially transparent to microwaves, so all the energy transmitted by a radiating device (a microwave applicator) reaches the pavement surface. Unfortunately, the common paving materials are inefficient microwave absorbers. The incident energy penetrates the pavement and the earth below, with only a very small fraction being dissipated near the top of the pavement where it is needed. Ice disbonding becomes feasible only if the pavement surface is coated with a microwave-absorbing overlay.

The existence of radar absorbing materials (RAM) provides assurance that it is possible to absorb incident microwave energy in a very thin layer of material. These materials are far too costly to be considered for runway coating. In seeking affordable absorber materials we considered carbon, and, in particular, coal as a potential component of an absorber overlay. This material had to be rejected because of its poor mechanical properties; it crumbles under compression. A series of experiments led us to a formulation containing asphalt, aggregate (fine crushed stone) and iron particles. This formulation appears to have mechanical properties (friction and load-bearing capability) comparable to conventional resurfacing materials, and it absorbs microwave energy effectively and converts it to heat.

This program involved a combination of experiment and computer simulation. The experimental program used microwave ovens and small-scale pavement/absorber/ice samples for comparative tests of various microwave absorber formulations. A 20 kw microwave generator/applicator was used for larger scale experiments. Computer simulation paralleled the experimental program. The simulation was based on a finite-element model of the ice/absorber/pavement strata, with one-dimensional microwave propagation and one-dimensional heat flow. Within the ice region

close to the pavement the substrata elements were 10 μm thick, so melting could be tracked to the nearest 10 μm.

In order to place the heat energy generated by microwaves close to the bottom of the ice, it is essential that the absorber layer be quite thin (e.g., 2 mm). To trap the microwave energy within the absorber layer, an electrically conducting layer can be placed between the absorber and the pavement. This layer might be electrically conducting paint.

Realistic values of duration of microwave irradiation are less than 1 second (typically 0.5 second). Longer values correspond to either very slow travel rates or unrealistically long microwave applicator apertures. We feel that 80 kW/m^2 represents a practical upper limit on microwave power density. A deicing machine with a 5 m^2 applicator aperture would require a total output of $5 \times 80 = 400$ kW of microwave power. If the magnetron efficiency is 50%, a diesel-powered generator with 800 kW output would be needed to supply the prime power. The bank of magnetrons with their microwave plumbing and controls would weigh about 12 tons. The diesel-powered generator would weigh about 11 tons. If the applicator aperture is 2.5 m wide and 2 m long (in the direction of travel), the travel rate would be 4 m/s or 8.9 mph to provide 0.5 second irradiation duration. This corresponds to a surface clearing rate of 10 m^2/s.

Early simulations seemed to indicate that the 40 kJ/m^2 energy density (80 kW/m^2 for 0.5 s) would disbond ice at pavement temperatures as low as -5°C. Laboratory experiments seemed to require higher energy densities, but there were a number of parameters in the experiments that were difficult to measure accurately. Recent efforts to explain the discrepancy between experiment and simulation, revealed a fault in the simulation. With the simulation corrected, new simulation runs were conducted with the most effective absorber configuration (2 mm absorber thickness, and a microwave-reflecting layer under it). These runs produced only a 20 μm melt zone for a power density of 80 kW/m^2 and 0.5 second irradiation duration, with a pavement temperature of -1°C. When the pavement temperature was dropped to -3°C, no melting occurred (perhaps some melting would take place, but not enough to melt the first 10 μm finite element).

It would, of course, be possible to raise the microwave power density or the irradiation duration to produce disbonding at lower temperatures, but this would necessitate deicing machine sizes or travel rates that are beyond the range of practical values. We are therefore forced to conclude that microwave disbonding of ice from an area the size of an airport runway is not feasible now. As higher power, more efficient microwave energy sources, which are lighter in weight and cost less, become available in the future, this evaluation should be done again.

SECTION I

INTRODUCTION

A. Background

While snow is readily removed from pavement by plowing or scraping, the removal of ice presents an entirely different problem, for ice is firmly bonded to the pavement. Removal of ice by scraping is impractical for two reasons; first, the force required is very high[1], and second, it is essentially impossible to avoid leaving a thin layer of ice still bonded to the pavement after the bulk of the ice has been scraped away. The purpose of ice removal is to provide a nonslippery pavement surface, but even a very thin residual layer of ice leaves the pavement slippery.

The usual method of dealing with ice is to sprinkle it with a chemical (e.g., salt or urea) to induce melting. Often sand is added to improve traction. The use of chemicals to melt ice has come into disfavor for two principal reasons; first is the concern over the damage that chemicals do to the environment, and second is the concern over damage to vehicles. This latter is especially worrisome when the vehicles are aircraft splattered with chemical soup from the runways.

The program with which this report is concerned came about as a result of an Air Force solicitation for nonchemical means for removing ice from runways. Research Associates of Syracuse (RAS) had recently completed an investigation into the use of microwave energy for disbonding ice from roadways, under the Strategic Highway Research Program (SHRP) of the National Research Council. Although microwave disbonding appeared to offer a potential solution, the SHRP funding was insufficient to permit either the necessary experimental work or computer simulations. The SHRP work is covered by two reports [1,2].

In another program, microwaves had been used in the patching of highway pavement. Potholes were irradiated with microwave energy to dry the pothole surface. After filling the pothole with polymer concrete, microwave energy was employed to heat the concrete to induce rapid curing, producing, in a matter of minutes, a patch that could support traffic. Research Associates of Syracuse acquired the 20 kw microwave generator from that program for use in the program covered by this report.

B. Major Problem Areas Investigated

Prior to the award of this contract, the sponsor raised the following questions [3].

(1) What heat flow model will be used?

(2) What are the properties (including thickness) of the radar absorbing material (RAM) to be used?

(3) What problems arise as a result of the antenna (microwave applicator) being so close to the runway surface? How much power is reflected back into the applicator?

(4) How much energy is required to disbond a square meter of ice? How does the energy requirement vary with runway temperature?

(5) How much melting is required to disbond the ice?

(6) What is the time duration of the "window of opportunity" for removing the ice?

(7) What will the RAM cost? What are the parameters (size, RF power output, speed of travel) of a realistic microwave ice disbonding machine?

These questions were essentially the ones that RAS had hoped to be able to answer through the proposed program. They are discussed briefly here in order to clarify, (1) the extent to which tentative answers could be given on the basis of prior work (the SHRP program), and (2) the approaches taken by RAS to answer these questions in the course of the work reported here.

1. Heat Flow Computer Model

Initially, we expected that use of existing software would save time and cost. As a result of discussions with a consultant, Mr. Fred Wenthen of the General Electric Co., it became clear that modifying existing heat flow software to provide the required two-way cross-communication between the heat flow model and the microwave propagation model would be more expensive than developing our own integrated model containing both heat flow and microwave propagation effects. Section 3 of this report discusses our model in some detail.

a. Microwave Absorber Material Properties

It was clear at the outset that microwave disbonding of ice could be accomplished only by applying an overlay of microwave absorbing material to the pavement surface. Pavement materials (concrete and asphalt-based materials) are poor absorbers of microwave energy. Ice is essentially transparent to microwaves. Most of the incident energy applied to a normal pavement coated with ice would be dissipated deep in the pavement and in the earth below. To induce melting at the ice-pavement interface would require prohibitive levels of microwave power. It is therefore essential that an overlay layer of microwave absorbent material capture a large fraction of the microwave energy, convert it to heat and quickly conduct it to the ice-absorber interface. Information on the absorptivity of existing radar materials (RAM) is available, but these materials are prohibitively expensive. Moreover, they generally lack the required physical properties (durability and coefficient of friction). For these reasons, very high priority was assigned to the development of an effective microwave absorber material that would be affordable, and have acceptable physical properties. Section 2 of this report is devoted to this part of the program.

c. Microwave Applicator Design

This is not a conventional antenna design problem. The pavement is in the near field of the radiating structure, and the wave impedance of the ice-pavement-earth propagation medium is quite different from the impedance of free space. It is clear that the discontinuities in electromagnetic parameters at the various interfaces (air-ice-absorber-pavement-earth) will result in multiple reflections, and some of the reflected energy will flow back into the applicator. This is, in effect, a continuous wave (CW) situation; the reflections overlap in time and are not observable as separate entities. At the microwave generator output terminals[1] the combined effect of the outgoing wave and the multiple returning reflected components is to produce a resultant terminal voltage and a resultant current flowing out of the generator.

The ratio of the resultant voltage to the current defines an effective load impedance into which the generator feeds its energy. When the internal impedance of the generator is made equal to the complex conjugate of the load impedance, there is maximum power transfer. We have assumed that in an actual microwave deicing machine, there would be a capability for this kind of impedance matching, either by manual adjustment of a matching network, or by automated adjustment. In Section 3 there is a discussion of the impedance matching assumption built into the computer simulation.

c. Microwave Energy Requirement

The answer to this question depends on several other questions:

(1) What melt depth is required for disbonding?

(2) What fraction of the total energy is captured by the microwave absorber layer?

---

[1]The description given here is in terms of a generator with a pair of terminals connected to a transmission line. Actually, the generator feeds into a waveguide.

(3) What fraction of this captured energy is devoted to melting ice?

(4) How long must the minimum required melt depth persist (before refreezing occurs) in order to provide time for a scraper or other removal device to reach the disbonded ice?

Question (1) is discussed in Section 1.2.5. Question (2) is discussed in Section 2. Question (3) is discussed in Section 3. Question (4) is discussed in Section 6.

Note that the initial pavement temperature has a strong influence on the answer to question (3), for it affects the rate at which energy is conducted from the absorber downward into the pavement, and upward into the ice. Initial temperature, of course, has a strong influence on the rate at which refreezing occurs after the microwave applicator has passed.

d. Required Melt Depth

No solid information was available on this subject, although there had been speculation[5] that as little as 2 to 5 microns (2 to 5 μm). would result in disbonding. We were inclined to believe that perhaps the required melt depth would be considerably greater. Actually it is very difficult to answer this question. If one conducts a series of experiments in which progressively greater energy inputs are applied, up to the point where it is found that the ice layer is disbonded, the melt depth at which disbonding occurs remains unknown; it is essentially impossible to measure that depth. We felt that the best approach to this problem was to combine experiments with computer simulation. If the computer model is a realistic representation of the physical situation, then if one knows the input power density and the time at which disbonding occurs, the computer simulation could reveal the extent to which melting had progressed at the instant of disbonding.

e. Time Window Of Opportunity For Ice Removal

This question has practical implications for the design of a machine for clearing runways. Generally, the maximum melt depth does not occur at the instant at which microwave irradiation ceases. Melting continues as heat continues to flow out of the heated absorber layer into the melt zone, until at some point the process reverses, and refreezing of the melt water begins, usually at the ice-water interface. Refreezing can also take place at the water-absorber interface. This bottom side refreezing generally begins considerably later than top side refreezing, because the warm absorber continues to supply heat to the melt water. From an efficiency viewpoint, one would like to apply only enough energy to cause the maximum melt depth to be just equal to the depth required for disbonding. The maximum melt depth and its time of occurrence both depend on the applied energy density (applied power density times the duration of irradiation). If the desired melt depth occurs within a second or so, it would be feasible to make the ice removal device a part of a single integrated machine. If the desired melt occurs many seconds after irradiation, a separate ice removal machine would have to follow behind the microwave applicator machine.

f. Projected System Costs And Sizing of A Deicing Machine

At the beginning of this program, no solid answers could be offered to questions of this sort, for no affordable absorber material was known, and no computer model was available to simulate the combination of microwave heating and heat flow in the ice-absorber-pavement strata.

SECTION II

OVERLAY MATERIAL DEVELOPMENT

A. Microwave Penetration of Various Media

An electromagnetic wave passing through a lossy medium loses a fraction of its energy for every unit of distance traveled. The lost energy appears as heat. Thus, the energy of the wave decreases exponentially with distance. The term "penetration depth" is used to characterize the ability of materials to absorb electromagnetic energy. This is the depth to which an incident wave penetrates by the time its electromagnetic field intensity drops to $1/\epsilon$ times its initial value ($\epsilon = 2.718$ = base of natural logarithms). At that depth, the field intensity has 36.8% of its initial value. The power density in the wave is proportional to the square of the field intensity, so the power has dropped to 13.5% of its initial value.

The penetration depth for ice is so great that ice can be considered essentially transparent to microwaves. The common paving materials (concrete and asphalt-based materials) have large penetration depths. For instance, at a frequency of 2.45 GHz, the penetration depth for concrete is about 20 cm, and for asphalt it is about 50 cm [4]. Microwave energy absorbed deep within the pavement is largely expended in warming the mass of pavement in the region where the absorption occurs. A part of the heat originating there eventually reaches the surface, but it arrives too late to contribute to the very rapid melting that would be essential if microwave disbonding were to succeed. Thus, it is clear that an overlay layer with high microwave absorptivity would have to be applied to the pavement surface.

B. Radar Absorbing Materials

An obvious starting point in the search for overlay materials was to investigate radar absorbing materials (RAM), for it is known that materials exist that are capable of absorbing more than 90% of incident microwave energy within a layer only a millimeter or a few millimeters thick. The obstacles to the use of existing RAM were immediately evident; first, its very high cost per unit area, second, its dubious durability, and third, surface friction properties that did not appear promising.

C. Search For Affordable Materials

It was clear that, if the program were to succeed, an overlay material had to be developed from relatively inexpensive ingredients, and that the resultant physical properties (durability and friction) should be comparable to those of existing paving materials. Furthermore, the overlay, if possible, should be capable of being applied by methods similar to conventional resurfacing methods.

A few experiments were conducted on ferrites mixed with various binder materials. The microwave absorptivity of these materials was high, but this approach was terminated when it became clear that the material costs were unacceptably high. The next material considered was carbon. This material has served as a basis for the manufacture of electrical resistors and attenuators for many years. Moreover, coal is an inexpensive source of carbon. High microwave absorptivity has been reported[5] for coal from several mining sites within the U.S.

1. Carbon Based Absorber Experiments

Graphite powder subjected to tests at 2.45 GHz showed high absorptivity, but when the powder was mixed with a binder material, the absorptivity dropped drastically. Apparently, the graphite particles need to be in contact with each other in order to produce strong absorption of microwaves; the binder effectively isolates the particles from each other.

Experiments were then conducted on samples of coal of various lump sizes, with and without a binder. Microwave absorptivity appeared promising, but it was concluded that coal lacks the physical strength required of an overlay material; coal crumbles under compression.

2. Asphalt-Aggregate-Metal Mixtures

Next, mixes were formulated from asphalt, aggregate (crushed stone) and metal particles. With this combination of materials it was possible to obtain physical characteristics very similar to those of conventional pavement resurfacing materials. Simple comparative tests in a microwave oven showed that these materials were much more effective microwave absorbers than ordinary paving materials.

3. Microwave Absorber Parameter Measurements

At this point, quantitative measurements were essential in order to compare the microwave absorption properties of different formulations. Direct measurements of microwave energy input and quantity of heat generated are very difficult to implement. An indirect approach is to measure the electromagnetic parameters of the material, and then compute the microwave propagation constant which determines the absorption efficacy of the material. We were fortunate in having the support of consultant, Dr. Robert Birge, director of the Molecular Electronics Laboratory at Syracuse University. Dr. Birge has had considerable experience in the development of radar absorbing materials, and his laboratory is equipped with excellent instrumentation for measuring the electromagnetic parameters of materials at microwave frequencies. From the various absorber formulations created by RAS, those with promising physical characteristics were taken to the laboratory for measurement. Of those, the one with the most promising absorption properties was chosen for disbonding tests and for insertion into the computer simulation. The attenuation constant (real part of the complex propagation constant) was found to be

$$\alpha = 213 \text{ m}^{-1}$$

The penetration depth d as defined in Section 2.1 is simply the reciprocal of the attenuation constant.

$$d = 1/\alpha = 4.7\times10^{-3} \text{ m} = 4.7 \text{ mm}$$

The attenuation in decibels is

$$20\cdot\log(\epsilon^{\alpha}) = 18.5 \text{ dB/cm} = 1.85 \text{ dB/mm}$$

SECTION III

COMPUTER MODEL FOR SIMULATION

A. Computer Simulation of Ice Disbonding

The application of microwave energy to disbond ice from pavement results in a transient heat flow situation. The variable of ultimate concern is the thickness of the melt layer at the ice-pavement interface. It is essentially impossible to measure this variable experimentally. Moreover, the experimental work required guidance in the selection of parameters (microwave power density, duration of irradiation and absorber layer thickness) likely to lead to a successful outcome. For these reasons a mathematical model or simulation was an essential adjunct to the experimental program.

The computer model has two separate but interrelated parts, the microwave propagation model and the heat flow model. If no melting were to occur, the microwave propagation could be approximated as a steady flow situation in which the electromagnetic parameters of the propagation media are assumed to be independent of temperature. When melting occurs during the period of irradiation, the propagation model is altered, for the propagation parameters of ice and water are very different. For that reason, the heat flow model must be coupled to the propagation model, producing a propagation model with time-varying parameters. Likewise, the coupling of the propagation model to the heat flow model provides heat energy inputs to the layers of material through which the microwave energy passes. Data flow between the two models is indicated in Figure 3-1.

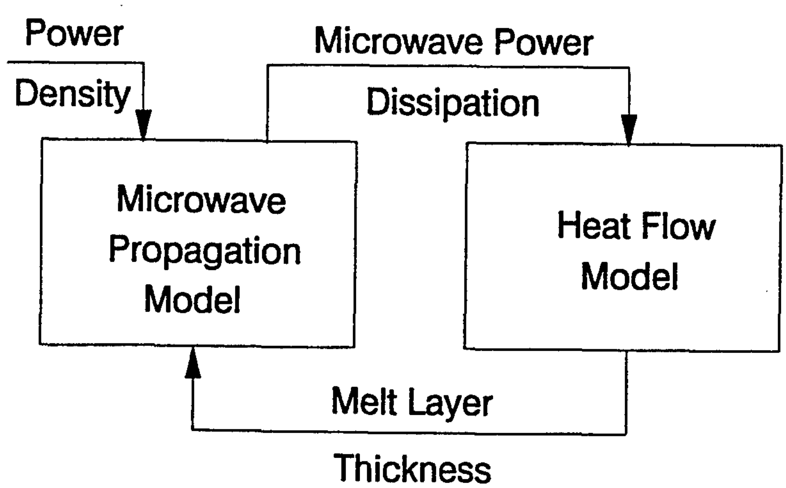

Figure 1. Computer Model

B. Propagation Model

As Figure 3-2 indicates, this is treated as a one-dimensional problem, that is, edge effects are ignored, and energy propagates in the y direction. The applicator distributes energy uniformly over its surface area as a downward propagating plane wave. At every stratum interface part of the incident energy is reflected, and the remainder is transmitted across the interface. This, of course, leads to multiple reflections which are taken into account by the model. The result is an effective wave impedance Z_{in}, into which the microwave generator feeds power. It is assumed that the generator source impedance Z_g is adjusted to be equal to the complex conjugate of Z_{in}, for this results in maximum power transfer from the generator. If melting occurs in a time less than the transit time of the applicator aperture across a given point, there will be some water under the applicator. The melt region will start somewhere behind the applicator leading edge, and its thickness will increase toward the trailing edge. The value of Z_{in} will be somewhat affected by the presence of the melt layer, but it will remain constant so long as the strata parameters, including ice thickness, are constant, and so long as the speed of travel is constant. Therefore, a manual adjustment of Z_g at the beginning of an ice clearing operation should assure maximum power transfer.

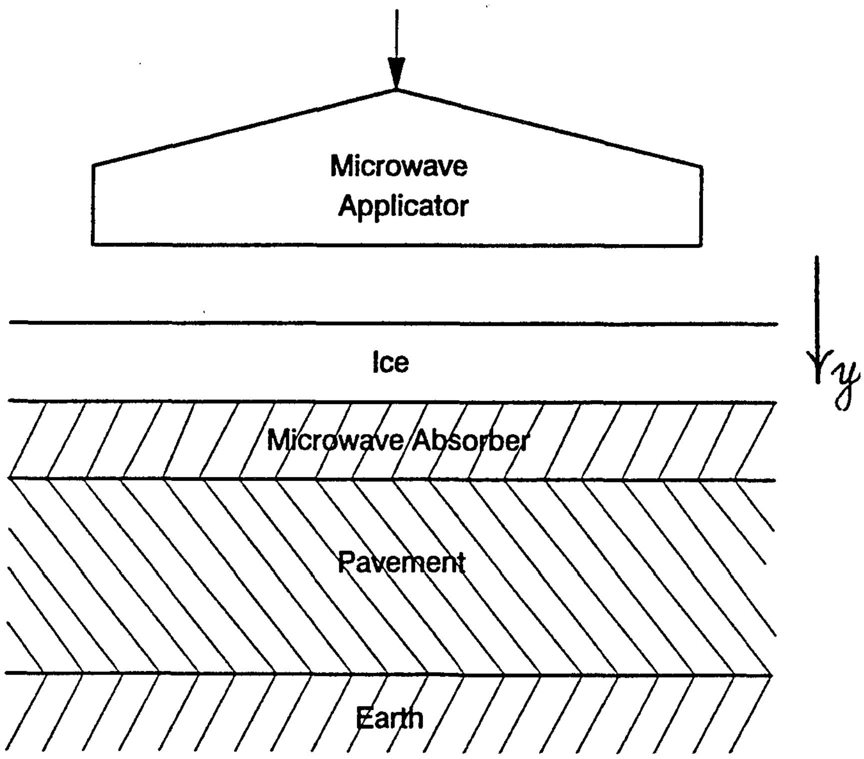

Figure 2. Microwave Propagation Model

C. <u>Propagation Analog</u>

The equations for the electric and magnetic field components of a plane wave have the same form as the equations for voltage and current on an electrical transmission line. Therefore the transmission line serves as a convenient analog of plane wave propagation through the strata of Figure 3-2. The wave impedance Z_0 and propagation constant γ of each medium have their counterparts in the characteristic impedance and propagation constant of the transmission line analog. The length δ of each transmission line segment is equal to the corresponding stratum thickness. The semi-infinite earth below the pavement is represented by the terminating impedance Z_e, equal to the wave impedance of the earth. Figure 3-3 shows the transmission line analog. For specific values of Z_0, γ and δ for each transmission line segment, and a specific Z_e, one can compute the input impedance Z_{in} at the input to the transmission line. Then with generator impedance Z_g set equal to the complex conjugate of Z_{in}, one can compute the voltage E and the current I at each interface. The power P flowing across a given interface is given by $E \times I^*$, where I^* is the complex conjugate of I. The difference between the power flowing across consecutive interfaces is equal to the power dissipated in the intervening line segment. Because of the multiple reflections, there are standing waves on each line segment, so one cannot assume that the power decays exponentially with distance from the upstream end of each segment. The simulation requires detailed information as to power dissipation within a given segment, so the transmission line analog in Figure 3-3 must be subdivided into many sub-segments.

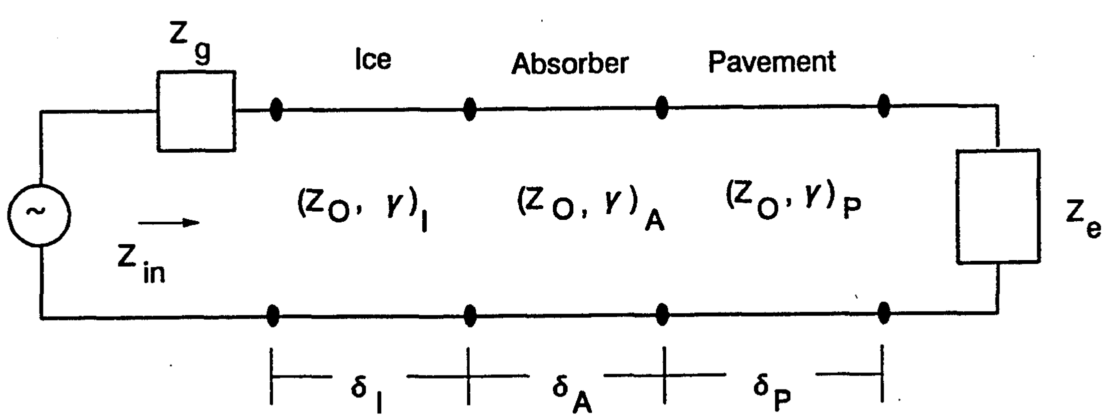

Figure 3. Transmission Line Analog

D. Four-Terminal Network Representation

To solve a problem of cascade-connected, dissimilar transmission line segments such as the one in Figure 3-3, it is convenient to represent each line segment as a four-terminal network (a network with a pair of input terminals, and a pair of output terminals) [6,7]. The network is fully characterized by a 2×2 matrix of complex parameters, A,B,C and D. For a network with bilateral symmetry such as a transmission line segment, A and D are equal. Moreover, the determinant of the matrix, (AD-BC), must equal unity. Knowledge of the complex permittivity and the complex permeability of a medium is sufficient to determine Z_0 and γ_1 of the medium, where γ_1 is a per-unit-length value of the propagation constant. The propagation constant γ for a given transmission line segment analog is just γ_1 multiplied by the line length δ, which is equal to the thickness of the corresponding stratum. A knowledge of Z_0 and γ is sufficient to determine the A,B,C,D parameters of the corresponding four-terminal network. Thus, it is a simple matter to subdivide a given line segment into many subsegments, and determine the A,B,C,D parameters of the network analog of each subsegment. One need only assign the proper length to each subsegment to determine the γ for the subsegment. The Z_0 value for the full segment is the same as the value of Z_0 for each subsegment. Then, as indicated above, one determines voltage and current values at each subsegment interface, and from these, the power dissipation within each subsegment. The division of each stratum into substrata for the heat flow model determines the subdivision of each transmission line analog in the propagation model. Each substratum in the heat flow model must receive the proper power dissipation from the propagation model. Likewise, for the ice stratum, the heat flow model must keep the propagation model informed as to the status of each substratum (whether it is ice or water). The model contains an option that is not shown in Figure 3-2; the presence or absence of a microwave reflecting layer between the microwave absorber and the pavement. If the reflectivity of this layer is high, most of the microwave energy is confined to the absorber layer.

Electromagnetic parameters for ice, water, pavement and earth were taken from handbooks and other literature sources. The parameters for the microwave absorber layer were based on measurements made at the Molecular Electronics Laboratory at Syracuse University.

E. Heat Flow Model

As in the propagation model, the flow (heat in this case) is treated as a one-dimensional problem; heat flow is in the y direction in Figure 3-2. Edge effects are ignored, so the model can be considered to represent a vertical column underneath a unit surface cell (e.g., one square meter) somewhere within the interior of the applicator aperture. Thermal parameters (conductivity, diffusivity and mass density) for ice, water, pavement and earth were taken from handbooks. Thermal parameters for the microwave absorber were based on the results of some simple experiments.

This is a finite element model in which the heat flow differential equations are replaced by finite difference equations, one for each node or substratum. Time is quantized into finite steps of size δt. The heat content per unit volume (enthalpy) of each node is tracked over time to determine node temperatures. The zero reference point for enthalpy is taken to be the point at which the temperature, initially below 0°C, just rises to the 0°C point. In ice, the node temperature remains at 0°C until the enthalpy reaches a value equal to the heat of fusion. Because melt layer thickness is the variable of ultimate concern, the substratum thickness of the ice near the pavement must be very small; we have typically used 10 µm or 10^{-5} m. This permits tracking of melt layer thickness to the nearest 10^{-5} m. It is impractical and unnecessary to use such fine subdivision throughout most of the strata of Figure 3-2.

The need for many very thin substrata in the vicinity of the ice-pavement boundary results in a requirement for very small time steps δt. To assure stability of the numerical integration process the following inequality must be satisfied.

$$\delta t \leq \frac{\delta y^2}{2\alpha_{max}}$$

where δy is the substratum thickness, and α_{max} is the largest thermal diffusivity in the model. For instance, if $\alpha_{max}=8x10^{-7}$ m^2/s, and $\delta y=10^{-5}$ m, we conclude that the requirement on the time step is

$$\delta t \leq 62.5 \mu s$$

We have used 60 µs time steps, so there are about 17,000 enthalpy updates per second of real time for each node. If the model has 50 nodes, there are 830,000 enthalpy computations for each second of real time. Even though the duration of the microwave input (the transit time of the applicator across a given point) is typically a second or less, the melt layer thickness generally increases for several seconds after irradiation ceases, because of continued heat diffusion out of the pavement. One is interested not only in the maximum melt depth, but also in the refreeze time, for this establishes the width of the time window available for ice removal after the microwave applicator has passed. When a significant melt depth is achieved, it is not unusual to find that complete refreezing requires 10 or more seconds. To assure effective disbonding, one would ideally time the removal process to occur at the time of maximum melt depth.

SECTION IV

ICE REMOVAL PARAMETERS

A. Parameters That Impact Disbonding

Our objective is to produce a melt zone of some depth δ between the ice and the top of the pavement. The value of δ required for disbonding remains uncertain, but we suspect that it is several tens of microns. As noted in Section 1.2.6, there is generally a considerable delay between the time at which irradiation ceases and the time at which the maximum melt depth is attained. In many cases that delay is so long that an ice removal device would have to lag quite far behind the microwave applicator if it were to attack the ice precisely where maximum melt depth is attained. If the ice removal device is to be an integral part of the deicing machine, its placement is constrained to locations no more than a few meters behind the microwave applicator. This fact could limit the efficiency of the deicing operation. Let us define a melt efficiency factor η as follows.

$$\eta = \frac{\textit{energy devoted to melting a layer of unit area and depth } \delta}{\textit{incident energy density at air-ice interface}}$$

Consider the case in which the ice removal device is an integral part of the deicing machine, lagging behind the microwave applicator by t_d seconds. If we stipulate that melt depth δ must be attained no later than t_d seconds after the microwave applicator has passed, we are, in effect, demanding a certain energy density sufficient to produce the desired melting at the specified time. The melt depth might eventually rise above the specified value at some time beyond t_d, but the energy consumed in producing the additional melt would be wasted, for the ice removal device would have passed by before the maximum melt could occur.

For estimating the amount of microwave power that would be required of a deicing machine to clear a specified area within a specified time, the following notation is used.

δ	=	specified melt thickness (m)
t_d	=	max delay after irradiation for attaining δ (s)
A	=	area to be cleared (m^2)
t_c	=	time permitted for clearing area A (s)
a	=	applicator aperture area (m^2)
t_i	=	duration of irradiation of any pavement spot (s)
w	=	applicator width (m)
d	=	applicator length in direction of travel (m)
T_0	=	initial pavement temperature (a negative value) (°C)
η	=	melt efficiency factor as defined above
E	=	applied energy density (J/m^2)

E_0 = energy per m^2 devoted to producing melt layer (J/m^2)
P = power output of applicator (w)
S = output power density = P/a (w/m^2)
R = rate of clearing = $A/t_c = a/t_i$ (m^2/s)

The melt volume per m^2 of pavement surface is simply δ m^3 or $10^6\delta$ cm^3. It requires[2] $10^6\delta|T_0|$ calories to bring the ice up to zero °C, and another $80\times10^6\delta$ calories to supply the latent heat of fusion. Therefore, E_0 is given by[3]

$$E_0 = 4.186(80 - T_0)\cdot10^6\delta \quad (J)$$

The power density from the applicator is S = P/a, and the energy density is $E = St_i = (P/a)\cdot(a/R) = P/R = Pt_c/A$ (J/m^2), and E_0 is given by the expression

$$E_0 = \eta E = \eta Pt_c/A$$

$$4.186\cdot(80-T_0)\cdot10^6\delta = \eta\frac{Pt_c}{A} = \eta\frac{P}{R}$$

so the required power output is[4]

$$P = \frac{4.186\cdot10^6\delta(80-T_0)R}{\eta} \quad (w)$$

It should be noted that η is not a constant, but is dependent on T_0; the colder the pavement, the greater will be the heat flow out of the absorber layer into the pavement and the ice, and consequently, the lower will be the value of η. Thus, initial pavement temperature has a much greater impact on the power requirement than is apparent in the above equation.

B. Melt Efficiency Factor η

The numerator of the expression for microwave power P is easily computed once δ and R are specified. It is simply the power required if all that power could be devoted to melting the layer of ice of thickness δ.

---

[2] T_o is nonpositive ($T_o \leq 0$).

[3] A calorie is equivalent to 4.186 Joules.

[4] Note that P is the total microwave power required to clear area A at rate R. P need not be supplied by a single machine.

In an example[4] the value of δ was assumed to be 5×10^{-6} m, and the area to be cleared was $A = 3.4\times10^{5}$ m^2. If the time allotted for clearing is 2 hours (7200 s), the rate of clearing is $R = 47$ m^2/s. The numerator of the power equation is then

$$P_0 = 1.967\times10^{8}\delta(80 - T_0)$$

With $\delta = 5\times10^{-6}$ m, and $T_0 = -1.0$°C we have

$$P_0 = 7.96\times10^{4}\ w = 79.6\ kw$$

The microwave power required is then

$$P = P_0/\eta$$

We were forced to depend on simulation results to arrive at values of the efficiency factor η. Clearly, η will depend on T_0 and on the parameters of the microwave absorber layer. It is also dependent on applied microwave power density and rate of travel.

For a given rate of travel v, the time lag of the ice removal mechanism behind the applicator is

$$t_d = x/v$$

where x is the spacing between the applicator's trailing edge and the ice removal device, and v is the velocity of travel. Ideally, one would adjust the applied power to produce the specified melt depth δ at time t_d after the applicator has passed. If, with maximum available power, the required δ could not be attained, then the travel velocity would have to be reduced to allow a longer irradiation time.

4.3 Deicing Machine Size/Speed Parameters

Suppose that the runway area A is to be cleared in time t_c. The microwave aperture area a is cleared in time t_i, the irradiation time, so the clearing rate is

$$R = A/t_c = a/t_i \qquad (1)$$

The clearing rate is simply the product of aperture width[5] w times the travel velocity v.

$$R = wv \qquad (2)$$

[5]Width W is the aperture dimension perpendicular to the direction of travel.

The time delay between the end of irradiation and ice removal is

$$t_d = x/v \quad (3)$$

where x is the distance between the trailing edge of the applicator and the ice removal device. The total time from onset of irradiation to arrival of the ice removal device is

$$t_{id} = t_i + t_d \quad (4)$$

Figure 4-1 is simply a plot of equation 1, showing irradiation time t_i as a function of clearing rate R, for three values of aperture area a. Figure 4-2 is a plot of equation 2, showing required travel velocity v as a function of clearing rate R, for three values of aperture width w. Figure 4-3 is a plot of equation 3, showing time delay t_d as a function of applicator/remover spacing x, for several values of travel velocity v. Within these plots, specific points can be chosen to indicate tentative machine configurations.

Point A on Figure 4-1 corresponds to a clearing rate of 10 m^2/s with a microwave aperture of 5 m^2 area. Point A on Figure 4-2 sets the aperture width at 2.5 m, resulting in a required travel velocity of 4 m/s. In Figure 4-3, the spacing x has a range of

$$2 \text{ m} \le x \le 10 \text{ m}$$

so the selected velocity results in time lags in the range

$$0.5 \text{ s} \le t_d \le 2.5 \text{ s}$$

In summary, the tentative parameters are:

R	=	clearing rate = 10 m^2/s
a	=	aperture area = 5 m^2
t_i	=	a/R = 0.5 s
w	=	aperture width = 2.5 m
v	=	R/w = travel velocity = 4 m/s
x	=	applicator/remover spacing = 2 to 10 m
t_d	=	applicator/remover time delay
	=	x/v = 0.5 to 2.5 s
t_{id}	=	$t_i + t_d$ = 1.0 to 3.0 s

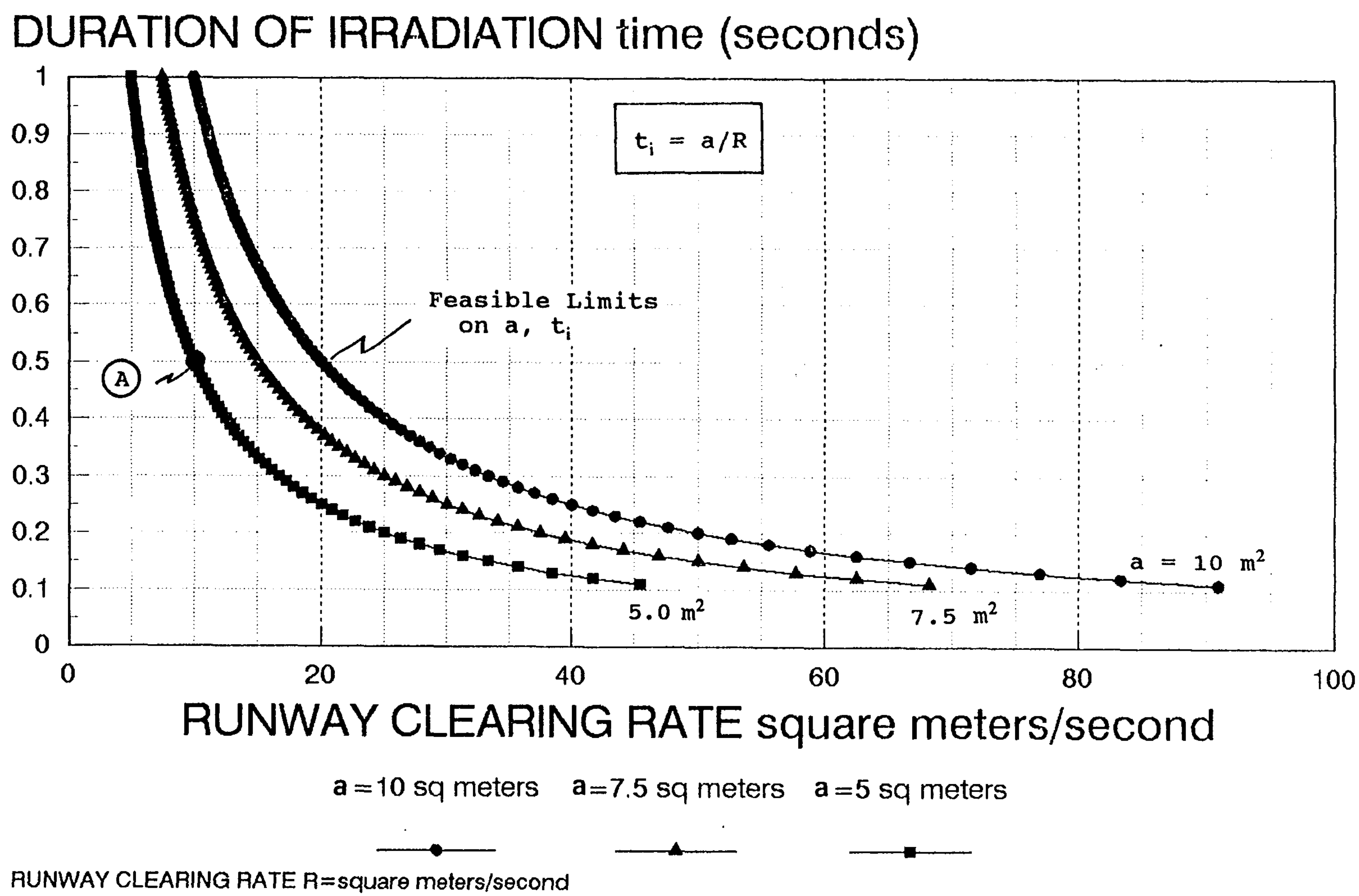

Figure 4-1. Duration of Irradiation of Pavement as a Function of Runway Clearing Rate and Aperture Area

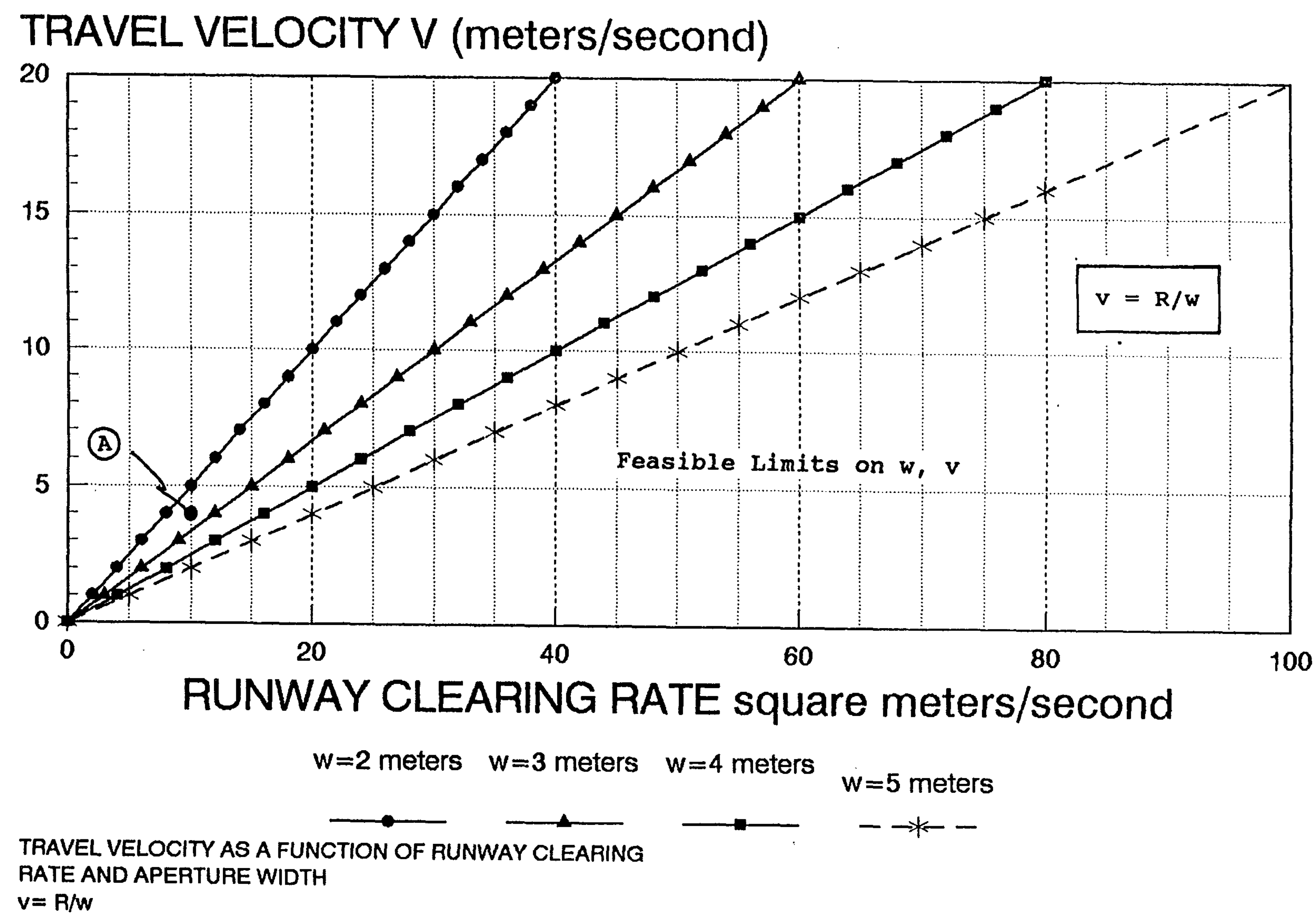

Figure 4-2. Travel Velocity as a Function of Runway Clearing Rate and Aperture Width

SECTION 5

LABORATORY EXPERIMENTS

5.1 Low Power Laboratory Tests

Early tests on materials made use of an ordinary microwave oven. These were comparative tests in which the samples, initially at room temperature, were placed on a rotating table in the oven and irradiated for a controlled period of time. At the end of the irradiation period, the surface temperature of the sample was measured with a thermocouple probe. Tests of this nature provided some guidance in the formulation of mixes of materials for pavement overlays. Obviously, these tests could not yield quantitative information as to absorptivity of materials, for even though the microwave power output of the oven magnetron was known, the power density at the sample location was not known. There are multiple reflections of the microwave energy between the metal walls of the oven enclosure. Part of the energy is absorbed by the test sample, part is dissipated in the metal walls and part is reflected back into the magnetron.

Once some tentative overlay formulations had been selected on the basis of these early tests, a second set of tests was begun. In these tests, circular concrete disks were coated with layers of the overlay materials of various thickness values. Then an ice layer of about one centimeter thickness was frozen to the top of the overlay. Figure 5-1 is a photograph of some of these disks. Frozen into the center of the disk of ice was a loop of nylon cord. The composite disk sample was then suspended from the nylon loop, directly under the open waveguide leading from the oven magnetron. The microwave energy emerging from the waveguide was incident directly on the top surface of the ice layer. The microwave energy passed through the ice into the overlay layer where part of the energy was absorbed. After some period of irradiation, a melt region developed at the ice-overlay interface, allowing the concrete disk to fall under its own weight. Measurement of the duration of irradiation required for the concrete to drop provided another method of comparing the relative absorptivities of various overlay formulations. Based on the nominal microwave power rating of the oven magnetron and the area of the waveguide aperture, the power density incident on the test sample was estimated at 60 kw/m^2. Even with this information and a knowledge of the duration of irradiation required for the concrete disk to drop free, it was still not possible to extrapolate to a value of energy density required for disbonding ice from pavement, nor was it possible to know the melt water depth required for disbondment.

It was always clear that by the time the concrete dropped free, a significant amount of melting had taken place. It seems likely that this amount of melting was considerably greater than would be required in removing ice from pavement. There are two reasons to believe this to be the case. First, the pull of gravity

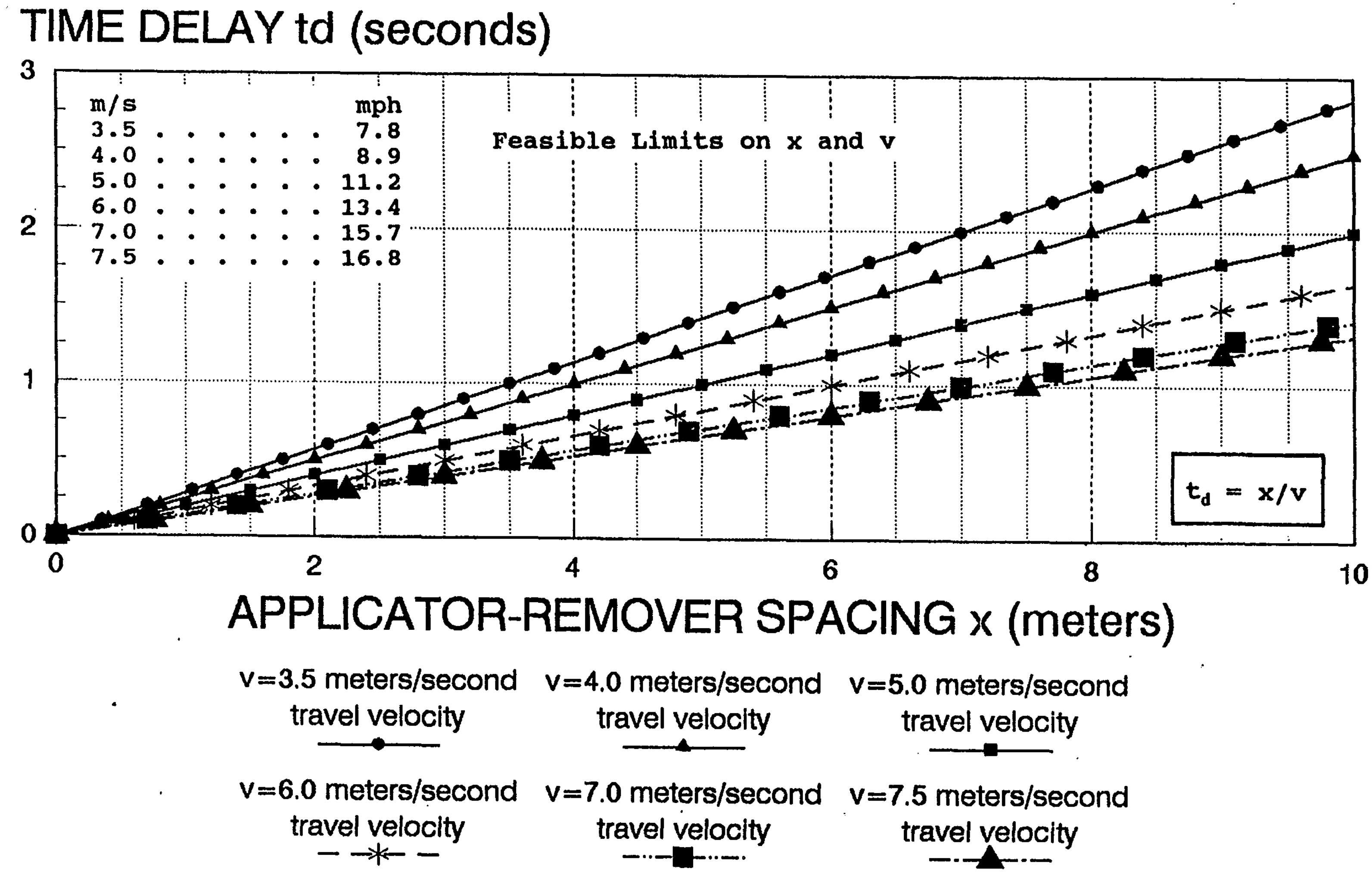

Figure 4-3. Delay Time as a Function of Applicator/Remover Spacing and Travel Velocity

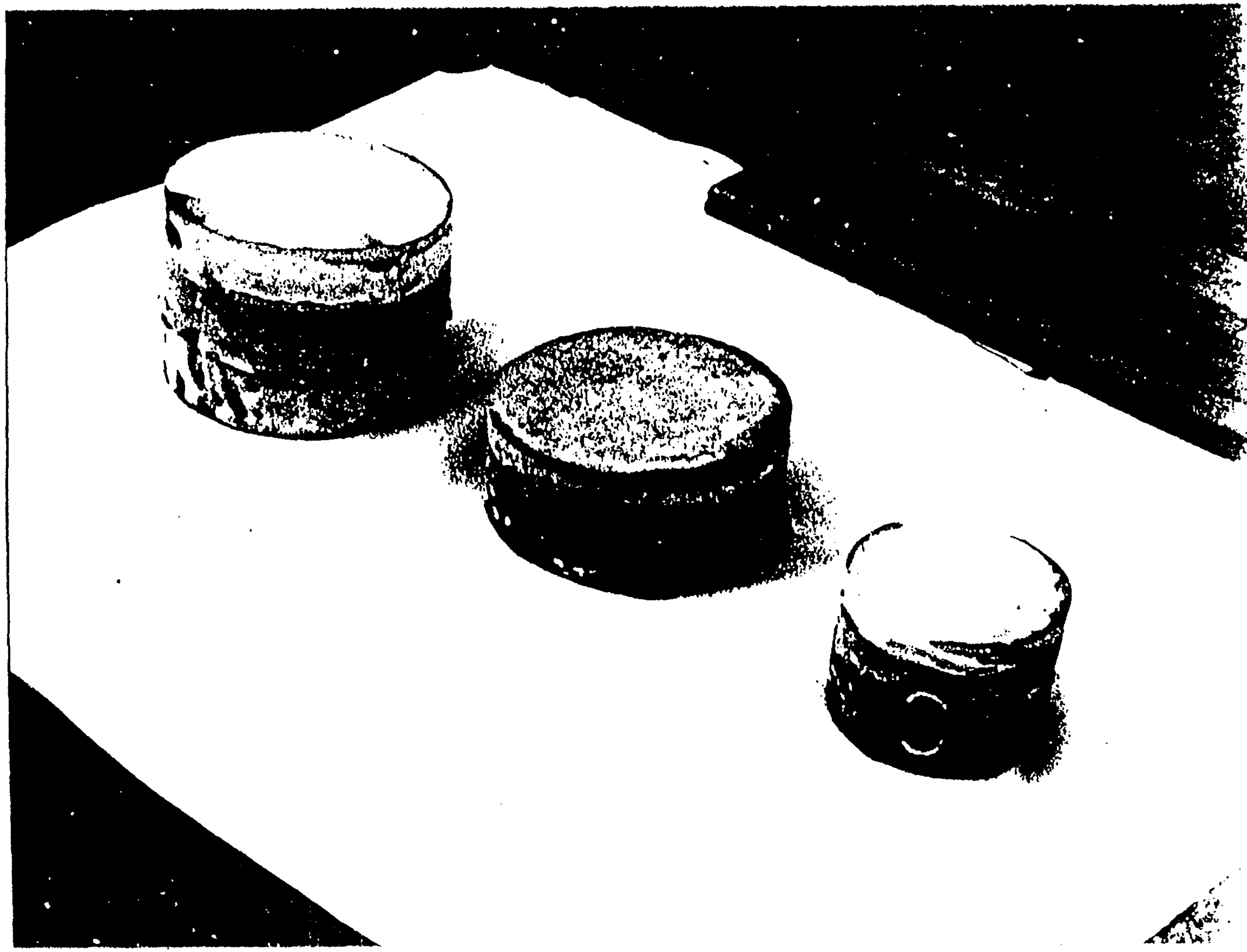

Figure 5-1. Pavement Sample With Ice

on the concrete disk was opposed by atmospheric pressure against the under side of the disk, and lack of such pressure on the upper side. The surface tension of the water at the outer edges of the very thin melt zone resists the atmospheric pressure (see Figure 5-2), until, at some increased melt depth, this equilibrium is overcome and the concrete drops. The second reason for believing that ice could be removed from pavement after less melting is the fact that any of several mechanisms can be applied to overcome the tendency for ice to remain in place. For instance, the thin layer of ice might be fractured by a "beating" or scraping mechanism, and then swept off the pavement by a stiff brush.

5.2 Higher Power, Larger Scale Laboratory Tests

The original plan for using the 20 kw microwave applicator was to drive it across a slab of ice-covered pavement at a controlled speed, with an ice scraper attached to the trailing edge of the applicator. In principle, one could begin at travel velocities low enough to provide a sufficiently long irradiation duration to disbond the ice. Travel velocities could then be successively increased up to the point at which disbonding failed. It was also intended that the force required to scrape the ice off the concrete would be recorded. Figure 5-3 shows the 20 kw microwave applicator on its mobile platform. The applicator for this unit consists of a bank of eight slotted waveguide radiators (see Figure 5-4), each radiating the output power of a 2.5 kw magnetron.

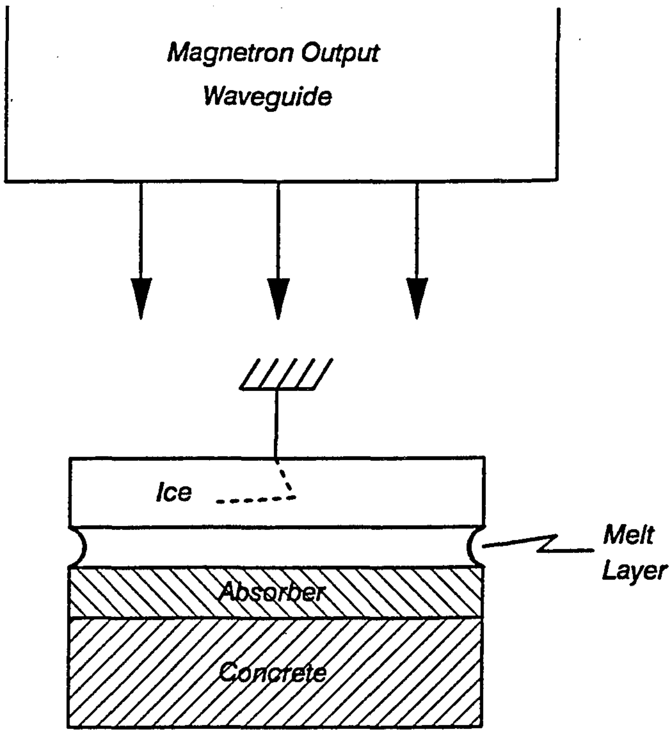

Figure 5-2. Melting Induced by Irradiation of Pavement Disk Covered by Ice Layer

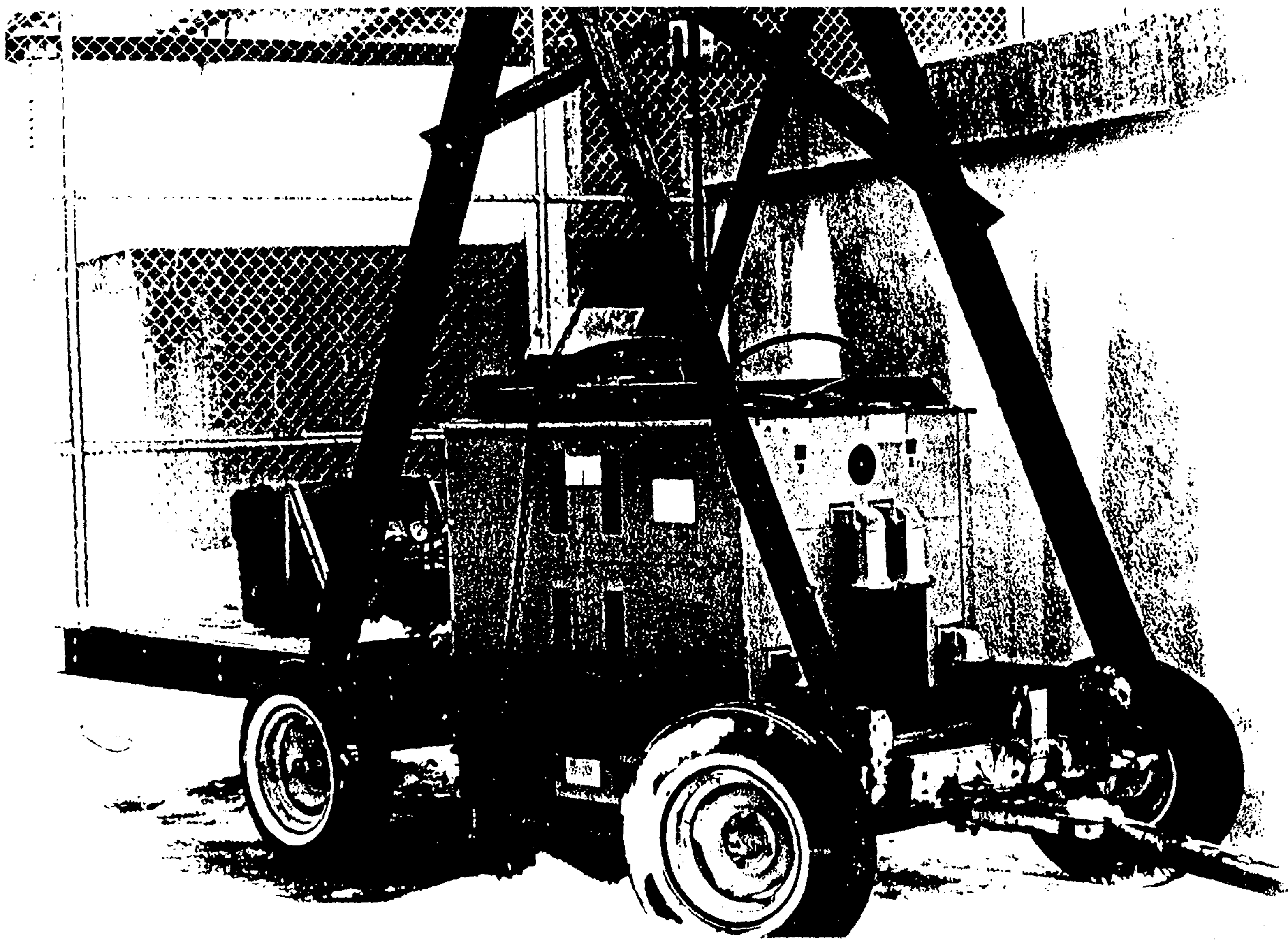

Figure 5-3. Twenty Kilowatt Microwave Applicator on Mobile Platform

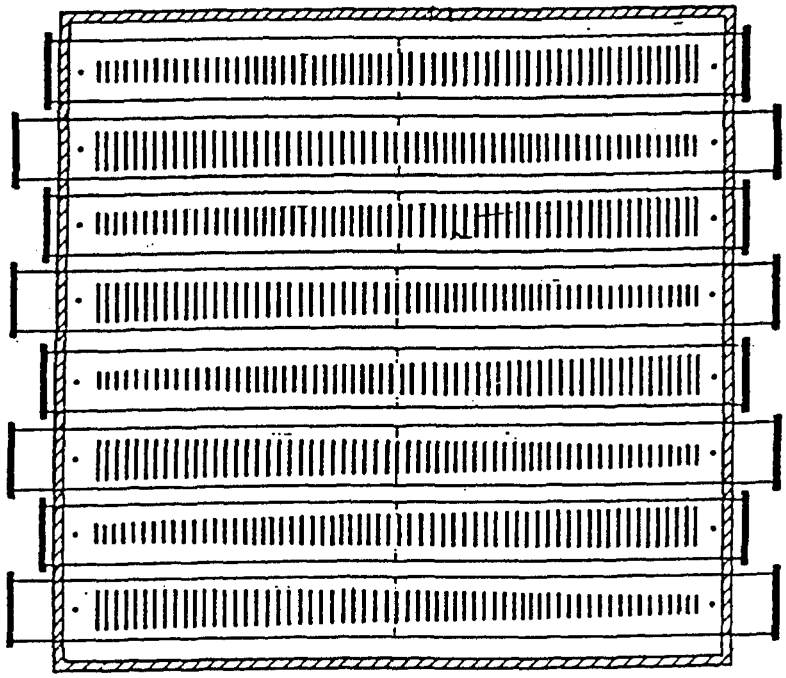

Figure 5-4. Slotted Waveguide Applicator

It soon became clear that there were better, less costly alternatives to this original scheme. One objection to the original scheme was the necessity to drag the cables carrying commercial ac power back and forth as the microwave applicator vehicle was propelled over the test slab. Another problem was accelerating this rather heavy vehicle up to the desired speed before reaching the test slab, and then stopping within a short distance after passing the slab. The cost of freezing ice on a slab the size of the applicator aperture was another obstacle. Computer simulations indicated that maximum melt depth occurred, in some cases, so long after irradiation as to preclude the placement of a scraper near the trailing edge of the applicator. Moreover, it seemed likely that a simple scraping operation would not be a satisfactory method of ice removal.

For all these reasons, it was decided that the size of the test slab would be scaled down, and that the microwave applicator would remain stationary, while a less massive test slab was moved under the applicator. The test slabs (one foot by two feet by four inches thick) were then of a size that could be accommodated in an inexpensive chest freezer.

With the narrower test slab, it became unnecessary to use the full aperture area of the 20 kw microwave unit. Waveguide extensions were fabricated so that the outputs of just three of the eight magnetrons were brought out to a convenient working level and coupled to their original slotted waveguide applicator elements. The three sections in parallel were sufficient to cover the one-foot width of the test slab. A wooden track was constructed to carry the test slab on a wooden carriage passing under the reduced-size applicator. Figure 5-5 is a photograph of this test setup.

As indicated in Section 4, realistic values of duration of irradiation are fractions of a second (e.g., 0.5 second). It was found that propelling the test slabs under the applicator at speeds that resulted in half-second irradiation times failed to produce disbonding. Power measurements on the magnetron outputs then revealed lower than expected power levels (power densities of only about 10 kw/m^2). Disbonding could be induced by holding the test slab fixed under the applicator and controlling the duration of the on-time of the microwave generator, but these durations were too long to correspond to realistic transit times of a deicing machine's applicator across a segment of pavement. The reason, of course, was the unacceptably low power density.

At that point, the applicator was modified by covering a portion of each slotted waveguide section, thereby increasing the power density in the region of the remaining open slots. This raised the power density of the reduced-size aperture to about 20 kw/m^2. The length of the reduced aperture (in the direction of travel) was then only about 15% of the length (2.0 m) of the aperture size discussed in Section 4. To achieve the proposed 0.5 second duration of irradiation, the travel velocity had to be reduced accordingly.

Experiments with 0.5 second irradiation times failed to produce disbonding. Simulation runs verified that the 20 kw/m^2 was insufficient to produce disbonding with 0.5 second duration of irradiation. Because the 20 kw/m^2 was the upper limit of the test apparatus, the only alternative was to increase irradiation times to values that resulted in disbonding. It was hoped that, by making simulation runs at the lower power levels and longer irradiation times, it would be possible to estimate the values of melt depth δ that resulted in disbonding in the laboratory experiments.

5.3 Overlay Friction Tests

Tests were conducted to compare the friction properties of the absorber overlay against an asphalt-based roadway sample. A small sled with a rubber layer on the under side was used to represent a vehicle tire in contact with the pavement. The horizontal friction force was measured with a spring balance. Table 5-1 shows the results of the tests. The friction force for the absorber was very nearly the same as for the conventional pavement under both dry and wet conditions.

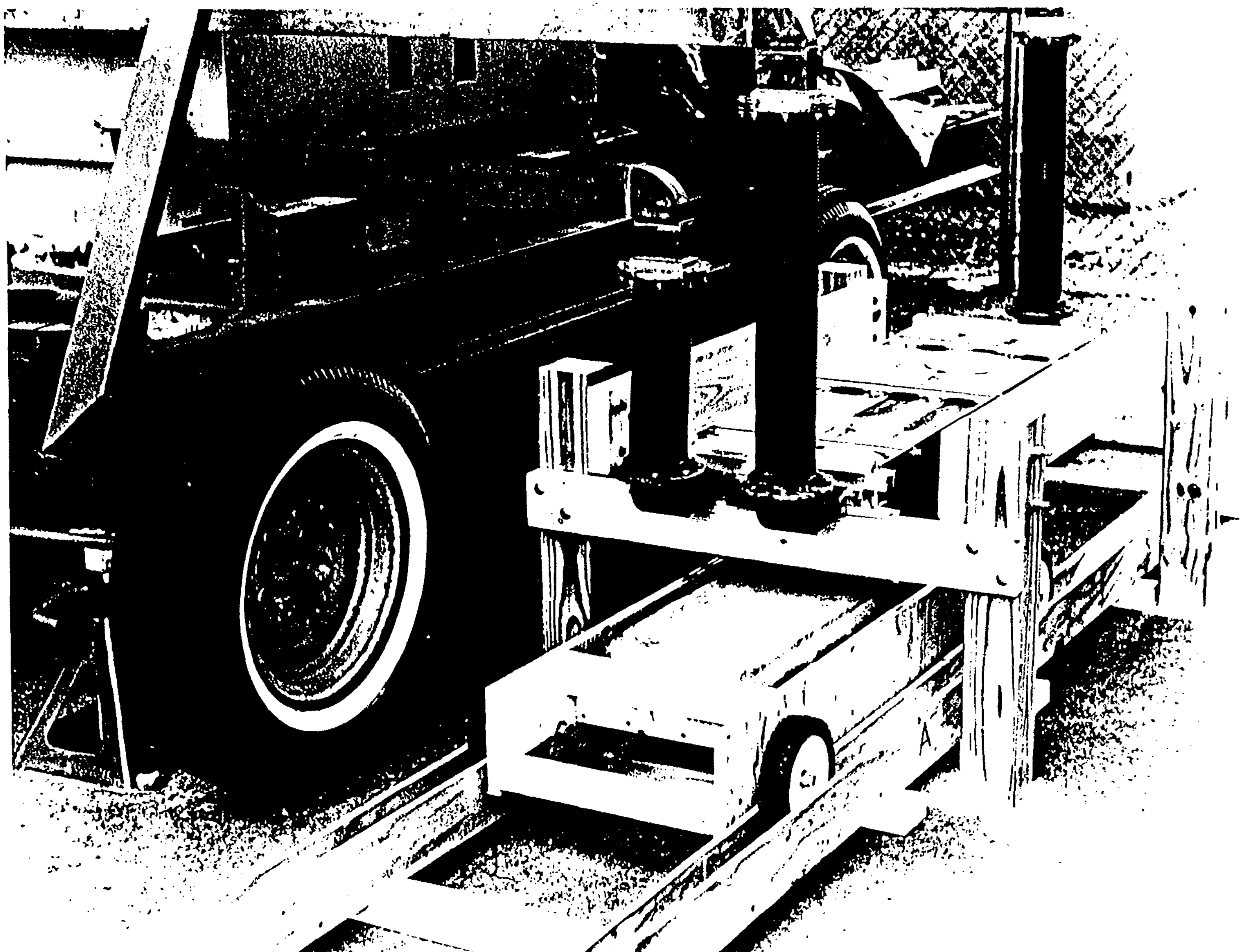

Figure 5-5. Photograph of Reduced Scale Test Setup

Table 5-1. Materials Friction Tests
(Force in ounces)

SAMPLE	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	AVERAGE
RAS MATERIAL (dry)	18.0	19.0	18.0	20.0	18.0	18.6
ROAD SAMPLE (dry)	17.0	17.5	17.0	17.5	17.5	17.3
RAS MATERIAL (wet)	18.0	17.0	15.5	16.0	15.5	16.4
ROAD SAMPLE (wet)	16.0	15.5	15.5	16.0	15.5	15.7

SECTION 6

SIMULATION RESULTS

6.1 Early Results

Simulation had led us to believe that melt depths of several tens of microns could be achieved at input energy densities compatible with the deicing machine parameters discussed in Section 4. We had felt that an input power density of about 80 kW/m^2 would be required, and that an aperture area of 5 m^2 defined the upper limit on size for a single machine. We believed that the 0.5 second irradiation time (corresponding to a clearing rate of 10 m^2/s) would produce disbonding for pavement temperatures as low as -5°C. A machine producing this level of microwave power (5×80=400kW) is probably at the upper limit of practicality. With 50% efficiency, an 800 kW diesel-powered generator would be required to provide the prime power. The bank of 27 magnetrons producing 15 kW each (together with cooling and waveguide plumbing) was expected to weigh over 12 tons, and the diesel-powered generator would weigh over 11 tons. To consider going to higher power levels would lead to a machine of unreasonable size.

Values of irradiation duration are bounded by practical considerations. Melting increases as the irradiation duration is increased, but values greater than one second correspond to either very low travel speeds or unrealistically long applicator apertures.

Although our laboratory experiments had not resulted in disbonding with energy inputs as low as the 40 kJ/m^2 that we were using in the simulations, there were a number of factors, not accurately measurable in the experiments, that we had felt could account for the discrepancy between experiment and simulation.

The simulation showed that the microwave energy had to be deposited in a very thin absorber layer (no more than about 2 mm thick) to achieve significant melting. Moreover, an electrically conducting layer was necessary under the absorber to trap the microwave energy. We had not perfected a method of applying such a thin absorber layer, so it was believed that the thicker layers used in the experiments could probably be blamed for lower melting efficiency than the simulations showed.

Within the last month of the program, a search for other possible reasons for the discrepancy between experiment and simulation revealed a fault in the heat flow model that caused an erroneous value of heat energy to be deposited at any interface between materials if a change in substratum thickness occurred at the interface. This error had caused excess heat to appear at the ice/absorber interface, and had been responsible for our optimistic view of the feasibility of microwave ice disbonding with power densities of the order of 80 kW/m^2 and irradiation times of 0.5 second.

6.2 Recent Results

With the corrected model, simulations were run, first at a pavement temperature of -1 °C, and then at lower temperatures, with each run at a temperature two degrees lower than the preceding value. It became clear that, with thick layers of absorber, little melting could be achieved, even at -1 °C.

Figure 6-1 shows the simulation results for two models in which absorber/pavement parameters have been selected to yield maximum melting. In both cases, the absorber overlay is only 2.0 mm thick, and an electrically conducting layer 0.1 mm thick is placed between the absorber and the pavement. In the first model, the pavement has a realistic value of thermal conductivity corresponding to that of concrete. With that model, a microwave power density of 80 kW/m^2 and an irradiation time of 0.5 second results in a maximum melt depth of only 20 microns. When the pavement temperature is dropped to -3 °C, the simulation reports zero melt depth. It is possible that a melt depth less than 10 microns would occur, but the substratum thickness in the model is 10 microns, so no melting is reported unless at least 10 microns of ice is melted.

The second model is intended only to show the effect of restricting the downward flow of heat into the pavement. An insulating layer (conductivity only 0.01 times the absorber conductivity) is placed under the absorber. This, of course, would not be feasible in practice, but it is a simple way to demonstrate the effect of heat loss into the pavement. Even in this model, a melt of only 40 microns is achieved at 0°C.

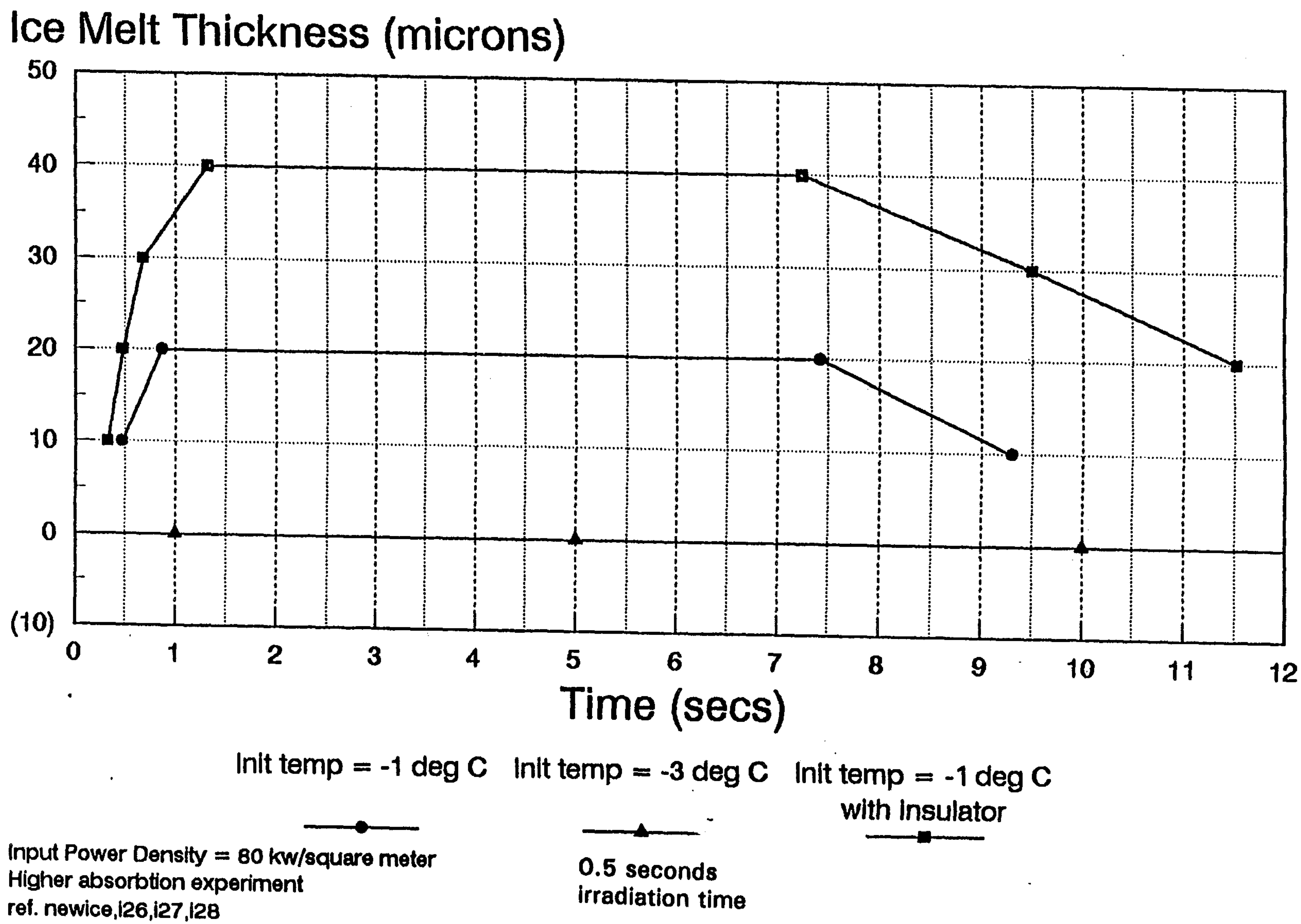

Figure 6-1. Simulation Results

SECTION 7

SUMMARY AND CONCLUSIONS

7.1 Lessons Learned

Because ice is essentially transparent to microwave energy, it is possible to transmit energy through ice into a microwave absorber overlay that has been applied to a pavement. This program led to the development of a relatively inexpensive formulation for the absorber overlay.

Laboratory experiments demonstrated that this approach enabled disbonding of ice from the pavement, with very little melting at the pavement surface. We are unable to conceive any method of measuring the depth of the melt zone, but we believe that several tens of microns would be required. It was for that reason that we chose to discretize the ice layer in the model into 10 micron increments. Although the 20 micron and 40 micron melt zones of Figure 6-1 persist for many seconds, we know that melts of smaller depth (under 10 microns) would persist for much shorter times when the pavement temperature is below about -1 °C. This is because, as initial pavement and ice temperature is lowered, the temperature gradient at the top and bottom of the thin melt zone is proportional to the difference between the melt water temperature (approximately 0 °C) and the temperature of the adjacent materials (pavement and ice). Thus, for the following two reasons, we did not see fit to investigate melts of less than 10 microns:

(1) Our doubt that 10 micron melts would result in disbonding.

(2) Our doubts that such thin melt zones would persist long enough to permit ice removal.

7.2 Prognosis For Improvements

Our laboratory experiments involved overlay layers of the order of a centimeter in thickness. We ran simulations with a thickness value of as little as 2.0 mm. For the absorber formulation developed by RAS, the 2.0 mm thickness value seemed to us to be less than could be used in practice, because of the difficulty in applying such a thin layer, and because of doubts concerning its durability, even if it could be applied.

The attenuation constant of the microwave absorber is proportional to the operating frequency, provided that the electromagnetic parameters (complex permittivity and permeability) do not vary with frequency. This means that penetration depth (defined in Section 2) would be inversely proportional to the operating frequency. This leads to the question as to the feasibility of going to much higher operating frequencies, perhaps so high that the penetration depth in ordinary pavement would be in the millimeter range. If this were done, one might dispense with the special absorber overlay. We remarked in section 2 that the penetration depth in concrete is about 20 cm at 2.45 GHz. If the above frequency dependence were to hold true at higher frequencies, one would have to increase the frequency by the ratio of 20 cm to 2.0 mm in order to reduce the penetration depth to 2.0 mm. This is an increase of 100:1, requiring an operating frequency of 245 GHz (a wavelength of 1.2 mm). No high power microwave generators exist at such short wavelengths.

With the absorber layer approaching zero thickness, the thermal time constants of that layer would tend to drop out of the picture, resulting in almost instantaneous flow of heat from the absorber upward into the ice (or water), and downward into the pavement. The rate of heat flow (over a short time span) in each direction would be proportional to the thermal conductivity of the material into which the heat flows. Let k_i and k_p respectively represent the conductivities of ice and pavement, and let q_i and q_p represent the quantities of heat conducted into the ice and the pavement in some short time interval after irradiation begins. The fraction of the heat energy going into the ice is

$$\frac{q_i}{q_i+q_p} = \frac{k_i}{k_i+k_p}$$

This is a pessimistic estimate, for the ice would not rise above 0 °C, whereas the pavement temperature would begin to rise, along with the temperature of the bottom of the absorber. But the bottom of the absorber would not experience any great temperature rise, because the absorber would be so thin that its temperature throughout would tend to be held close to the ice temperature. As soon as a thin melt zone appears, the conductivity of the upper medium would begin to shift from k_i to k_w, the conductivity of water, and the fraction of the heat flowing upward would begin to approach

$$\frac{q_w}{q_w+q_p} = \frac{k_w}{k_w+k_p}$$

In the simulation, the conductivity values were

k_i = 2.215 W/m°C
k_w = 0.561 W/m°C
k_p = 0.685 W/m°C

With these conductivities, the heat flow fractions are

$$\frac{q_i}{q_i+q_p} = 0.76$$

$$\frac{q_w}{q_w=q_p} = 0.45$$

If we use the smaller of these two fractions as a very optimistic estimate of the melt efficiency factor η (see Section 4) and if we demand a melt depth of

$$\delta = 40\ \mu m = 4\times10^{-5}\ m$$

the required energy input per square meter would be

$$E = \frac{E_0}{\eta} = \frac{4.186(80 - T_o)\cdot 10^6 \delta}{\eta} \quad (J)$$

For initial temperatures near 0 °C, we have

$$E = 2.98\times10^4 \quad (J)$$

For an irradiation duration of 0.5 second, the required input power density is

$$P = 2.98\times10^4/0.5 \text{ watts per square meter} = 60\ kW/m^2$$

Note that this is of the same order of magnitude as the power density that was used in the model in which the thermal insulator was placed below the microwave absorber (see section 6).

7.3 Practical Implications

The simulation models discussed in Section 6.2 are rather idealized. The concept of placing a thermal insulating material below the microwave absorber would be difficult to realize. The very thin (2 mm) absorber layer with an underlying reflecting layer may be in the realm of possibility, but its durability is questionable. As the simulation shows, even this rather optimum model yields a melt efficiency that is inadequate to produce disbonding at temperatures below -1 °C if the microwave power density is limited to 80 kW/m^2 and the irradiation time is limited to 0.5 seconds. Higher power densities would require a greater total power output than is practical for a deicing machine capable of clearing pavement at an acceptable rate. The inevitable conclusion is that microwave disbonding of ice is not now feasible for dealing with pavement areas as large as airport runways. However, as higher power, more efficient microwave energy sources, which are lighter in weight and cost less, become available in the future, this evaluation should be done again.

LIST OF REFERENCES

1. Ice-Pavement Bond Disbonding--Surface Modification Disbonding, Report No. SHRP-H/FR-90-2, Strategic Highway Research Program, National Research Council.

2. Microwave Ice Disbonding, SHRP H-204, First Year Report, RAS TR 89-599, March 1990, Subcontract: MTU-41995, Contract: SHRP-88-H204, Report to Michigan Technological University.

3. A Quick Look Assessment of Ice Removal From Runway Surfaces Using Microwaves, by Major Larry Moreland, Electromagnetics Assessment Branch, Phillips Laboratory, Kirtland AFB, July, 1991.

4. Physical Alternatives To Chemicals For Highway Deicing Vol. I-A: Phase I Results- Development Of Concepts, (Appendices A through J) Interim Report No. 1, 6 August 1976 - 31 May 1977, Contract No DOT-FH-11-9126, MRI Project No. 4284-D, by Midwest Research Institute, for Federal Highway Administration, U.S. Department of Transportation.

5. Nelson, S.O., et al, Frequency Dependence Of The Dielectric Properties Of Coal-Part II, Journal of Microwave Power, 16(3 and 4) 1981.

6. Guillemin, E.A., Communications Networks, Vol. II, The Classical Theory of Long Lines, Filters and Related Networks, John Wiley and Sons, Inc. 1935.

7. LePage, W.R., and S. Seely, General Network Analysis, McGraw-Hill, 1952.

APPENDIX A

DETERMINATION OF THERMAL PARAMETERS
OF MICROWAVE ABSORBER

Because the microwave absorber is a mixture of three constituents (asphalt, aggregate and iron particles), its thermal parameters are not accessible from engineering handbooks. Two simple experiments were devised to measure the values of the thermal conductivity and the specific heat capacity of the absorber material.

Thermal Conductivity Measurement

This measurement procedure was contrived to yield a relative conductivity value (conductivity of absorber relative to the conductivity of a reference material accessible from handbooks). The reference material chosen was concrete for which we used the following handbook value:

k_c = thermal conductivity of concrete = 0.685 w/m°C

The test apparatus is shown in Figure A-1. The copper slab, initially at temperature T_{c0}, well above room temperature, is brought into contact with a slab of the material under test (concrete or absorber) at time t = 0, and the transient drop in temperature T_c of the copper plate is recorded.

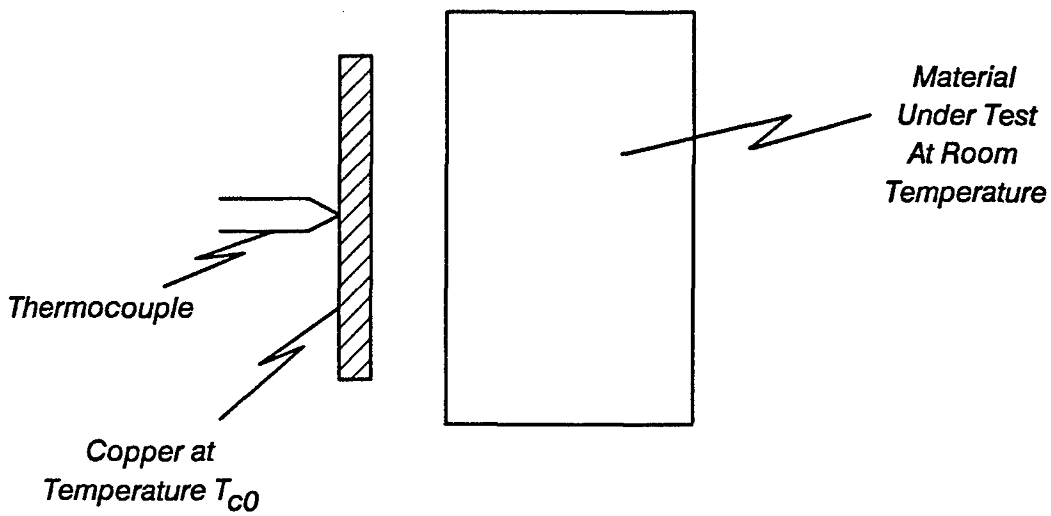

Figure A-1. Conductivity Measurement Setup

Because the copper slab is thin, and because its conductivity is so high (approximately 400 w/m°C), the measured temperature is essentially equal to the temperature at the interface between the two slabs. The conductivity of copper is several hundred times the conductivity of concrete (and the absorber material), so the rate of heat flow out of the copper into the material under test is governed by the conductivity of the material under test. Because the copper slab is thin, and because its specific heat capacity is low (about 400 J/kg°C), its temperature drops rapidly when the two slabs are brought into contact.

Figure A-2 depicts the temperature transient of the copper slab for two different test materials, for identical values of initial temperature difference between the slabs. The early portion of each transient is essentially linear, so the slopes are obtained by measuring $\Delta T/\Delta t$ as shown in Figure A-1.

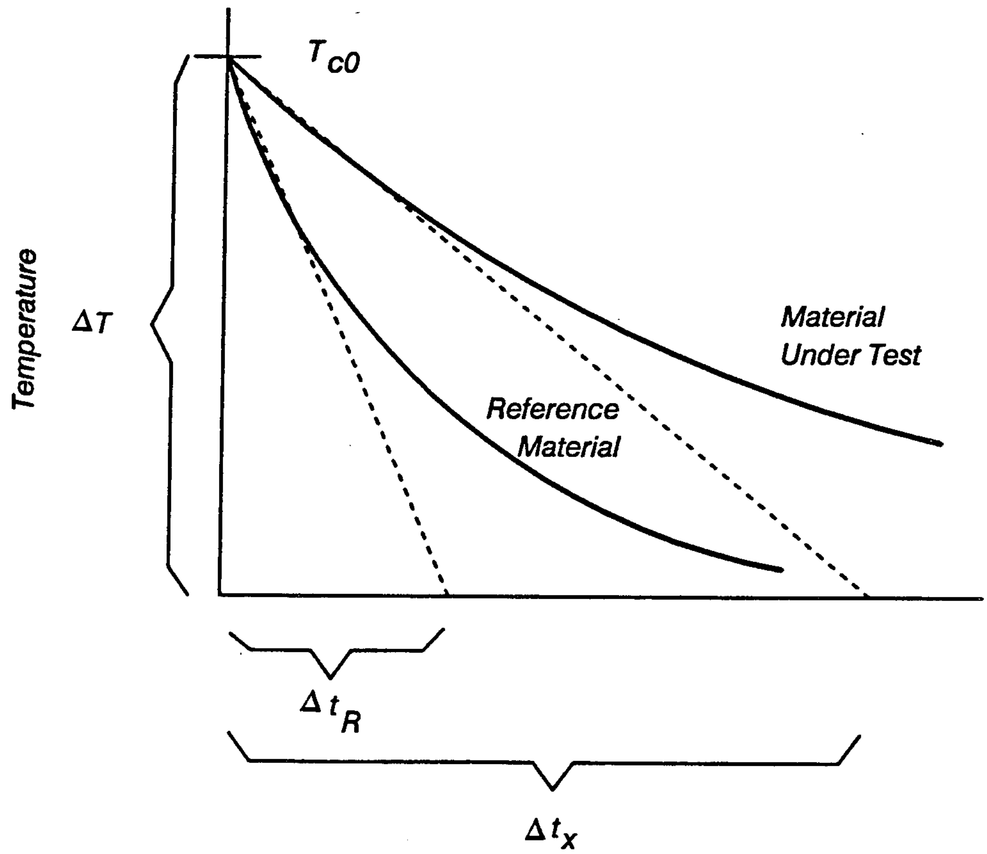

Figure A-2. Temperature Transients

The slope is directly proportional to $k\Delta T_0$, where k is the thermal conductivity of the material under test, and ΔT_0 is the initial temperature difference between the copper slab and the slab under test. The slope is inversely proportional to ρC_p, where ρ and C_p are respectively, the mass density and the specific heat capacity of the material under test.

Specific Heat Capacity Measurement

This measurement was made by immersing a heated sample of the material under test in a measured volume of water, and allowing this combination to reach equilibrium temperature. The container is a thin styrofoam bowl. The specific heat capacity of the material under test is obtained from the following equation.

$$m_x C_x (T_x - T_f) = (T_f - T_w)(m_w C_w + m_c C_c)$$

The symbols in this equation have the following meanings.

m_x = mass of material under test
C_x = specific heat capacity of material under test
m_W = mass of water
C_W = specific heat capacity of water
m_c = mass of container
C_c = specific heat capacity of container material
T_x = initial temperature of material under test
T_w = initial temperature of water and container
T_f = final (equilibrium) temperature of the combination

This relation, of course, neglects heat loss from the walls of the container, but this loss is small if the temperatures T_w and T_f are not very different from the ambient temperature.

Summary of Thermal parameter Measurement

From the measurements described above, we arrived at the following values for the thermal parameters of the microwave absorber material.

k = thermal conductivity = 0.30 w/m°C
C_p = specific heat capacity = 1855 J/kg°C
ρ = mass density = 2600 kg/m^3
α = $k/\rho C_p$ = thermal diffusivity = 6.22×10^{-8} m^2/s