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The report consists of a paper entitled "Snow Electromagnetic Measurements" by W. I. Linlor, J. L. Smith, F. D. Clapp and D. J. Angelakos presented at the Workshop on the Microwave Remote Sensing of Snowpack Properties held on May 20-22, 1980 at Fort Collins, Colorado.

SNOW ELECTROMAGNETIC MEASUREMENTS*

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ABSTRACT

An electromagnetic system is described for measuring the dielectric constant and attenuation of snow samples in the frequency range of 4 to 12 GHz. System components consist of a swept-frequency source, microwave horns, network analyzer, and XY plotter. Procedure in calibrating the effect of wetness on the snow properties is described. Equations are given that express the experimentally determined relation between attenuation per unit length and volume percent wetness at any frequency between 4 and 12 GHz. Permittivity can be calculated from the snow density, attenuation per unit length, and frequency. Some applications of the techniques are described such as runoff forecasting from mountain snowpacks.

INTRODUCTION

The measurement of mountain snowpacks is one part of the NASA programs for remote sensing of earth resources, employing active and passive electromagnetic systems. To plan experiments and to interpret results, one must have values for the permittivity and attenuation of snow for the range of wetness encountered under natural conditions. The frequencies of interest start at a few gigahertz (GHz).

Published information regarding the attenuation of wet snow in the GHz region is extremely limited. Cumming (ref. 1) gives curves relating the loss tangent of snow to liquid-phase water for two densities at the frequency of 9.375 GHz. Sweeny and Colbeck (ref. 2) measured the dielectric constant and loss factor at 6.0 GHz for wet snow, their values of wetness ranging from 0 to 24% by volume. They also performed tests using glass beads as the host medium in place of snow. Linlor (ref. 3) measured the permittivity and attenuation of wet snow between 4 and 12 GHz.

The present paper addresses topics of interest to snow specialists, in the context of the Linlor paper (ref. 3), such as calibration procedures for

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obtaining snow samples having known amounts of liquid-phase water. Previous publications (refs. 4-14) are listed as references without discussion because this is not intended to be a "review paper." However, the data of references 1 and 2 are compared with our results.

SNOW SAMPLES HAVING KNOWN WETNESS

The preparation of samples of snow having known amounts of liquid-phase water is a difficult problem. Sweeny and Colbeck (ref. 2) employed a "capillary pressure system" in which the snow sample was first saturated with ice water, then drained, using a porous plate under a negative pressure gradient. The water content was calculated by taking the difference between the water added and that removed.

Jones, Rango, and Howell (ref. 15) measured the water content in naturally occurring snow rather than preparing samples. They employed a "cold calorimeter" to measure the heat absorbed in freezing the liquid-phase water. Such a measurement does not provide information as to the effect on the dielectric constant and attenuation produced by liquid-phase water when present in snow.

Our approach is based on adding known amounts of water to initially dry snow, mixing thoroughly, and measuring the sample to obtain the permittivity and attenuation in the frequency range of 4 to 12 GHz.

SNOW SAMPLE SIZE

Large samples were chosen so that crystal orientation effects would be averaged, and so that any inhomogeneities (if present after mixing) would also be averaged. A Plexiglas cell was used, having inside dimensions of 39.1 cm × 39.1 cm × 14.5 cm thick. The walls were 0.635 cm (0.25 in.) thick. Snow density was obtained from cell weights, full minus empty.

WATER ADDITION

Tests were made to determine how ice water should be added to dry snow to obtain a reasonably uniform final state. If feasible, the water should be added as "in nature," with downward diffusion producing the uniformly wet sample. For our purposes the rate of adding the ice water had to be sufficiently rapid to achieve at least several samples per day.

An exploratory test was made on a large cube of new, dry, homogeneous snow, approximately 1 m on each side, all of which had been deposited in a single storm. This block was isolated from a snowbank by digging vertical clearance channels, and a metal plate was inserted at the bottom. Ink-colored water was sprayed gently and uniformly on the top, at the rate of approximately 600 cm^3/min on the area of 1 m^2. The spray-water application was stopped when water was observed at the metal plate, and the snow block was examined. Upon removal of the sides of the block, it was found that the water had formed "veins" vertically down through the block, although it had been sprayed quite uniformly. The final distribution of water was distinctly non-uniform throughout the volume.

To check whether this type of vertical channeling occurs naturally or was produced because of the rate of addition of water, snowpacks were examined by carefully removing snow. Vertical "fingers" were found, originating at layers within the snowpack, having dimensions approximately 0.3 to 0.6 cm in diameter and vertical lengths of 5 to 10 cm. It was not known whether these fingers were produced solely by heat melting (sun and air) or if some unobserved (i.e., unreported) rain had occurred. This phenomenon is identified as a problem for further investigation because the presence of such fingers would obviously affect measurements via either active or passive microwave systems.

On the basis of the above information it was concluded that mechanical mixing of wetted snow samples is necessary to achieve uniformity in the final sample.

EFFECTS OF MIXING

Tests were made to determine whether the mechanical mixing of wetted snow would produce undesirable effects such as melting and major grain structure modification.

Dry snow samples were placed in a mixing chamber and vigorously stirred using manually operated wooden paddles. The force exerted on the snow averaged about 10 lb, acting through a distance of about 3 ft in 1 sec, as the maximum work rate. During 15 min of mixing, the average power was about half the maximum. The effect of mixing was measured by noting the increase in snow temperature, starting at, for example, -15° C, with a room temperature of -5° C. We found that the snow reached room temperature within 10 min or less, and remained at the room temperature despite mixing for an additional 15 min. The conclusion was that the mechanical mixing produced a rise in snow temperature of not more than 1° C.

The preceding conclusion is confirmed by calculation of the heat produced by mechanical work. The dry snow sample had a mass of 20,000 gm. The manual work rate (average) of 15 ft-lb/sec is equivalent to 20 W. For the time of 15 min, the energy is 18,310 J, or 4,380 calories. Since the specific heat of snow is about 0.5 calorie/gm/°C, the 20,000 gm of snow would be raised in temperature by 0.44° C.

If the dry snow were at 0° C, the energy of 4,380 calories would produce melting of 55 gm of snow (heat of fusion being 80 calories/gm), or about 0.3% wetness by weight. For snow of density 0.5 gm/cm^3, this represents a volume wetness of 0.14%.

In some cases the snow was mixed using motor-driven paddles. It is difficult to estimate how much of the motor power was transferred to the snow, but experimentally it was found that temperature of dry snow behaved similarly to the case of the manually stirred snow.

Examination of snow crystals at 8× magnification before and after the mixing did not show any significant change in structure.

Tests were also made to determine the effect of room temperature on the snow during the mixing time. The conclusion was reached that for 1 cm^3 of snow in the laboratory (no sunlight and no appreciable air motion) having temperature of +1° C, approximately 1% volume wetness is produced in 15 min. Obviously, to minimize this type of melting, samples having a large volume to surface ratio should be employed. Our samples (see above) had volumes of the order of 40,000 cm^3.

We estimate that the combined effect of mechanical work and ambient room temperature melting during snow mixing produced an uncertainty of less than 0.5% in the volume wetness.

CALIBRATION PROCEDURE

For calibration tests, snow samples were employed which had a known history and which had never experienced melting. For example, newly fallen snow at the temperature of -10° C was collected and placed in thermally insulated containers. Other collections of snow were placed in freezer chests for about 6 months at -15° C.

In preparation for calibration tests, the snow was brought to essentially 0° C by placing it in a waterproof container and surrounding it with moist snow (i.e., 0° C environment). When the snow was less than 1° away from zero, it was briefly stirred, placed in the test cell, and measured to confirm that it was dry. This test (without measurable attenuation) was performed on all calibration samples before water was added.

Next, a known amount of snow was selected, typically 20,000 gm. Water was chilled to 0° C, and 200 gm added and mixed; this produced 1% wetness by weight. After mixing for about 15 min, some of the snow was placed in the Plexiglas test cell and compacted to ensure uniform density. The snow-filled test cell was examined under a bright light to determine if it looked uniformly gray (transmitted light). The sample was then placed in a thermally insulated foam box and the EM measurements made (see below).

After being tested, the snow in the cell was returned to the table and the full (20,200 gm) supply received additional ice water, so as to encompass the desired wetness range. In some cases, 20% of the dry snow weight was added in the form of ice water to determine whether a single large step was equivalent to the sum of perhaps 10 small steps. Although the total mixing and exposure to ambient temperatures were different, we found that both procedures gave essentially the same results, providing that the ambient temperature was less than 1° away from 0° C.

Each sample was weighed after the EM measurements to provide the average density of the wet snow. The snow crystals were examined under low-power (8×) magnification before and after the EM measurements to determine average grain diameters. If the mechanical mixing produced any effects, they were not discernible at the low-power magnification, in comparison to natural snow.

INSTRUMENTATION

Phase shift and transmission loss were measured, using two identical Plexiglas containers, one as the reference unit (empty) and the other with the snow sample. The containers had inside dimensions of 39.1 cm by 39.1 cm in the plane perpendicular to the microwave beam, and a depth of 14.5 cm in the direction of the beam. The walls were 0.635 cm (0.25 in.) thick.

Three pairs of conventional microwave horns were used, each horn having nominal gain of 20 dB at its midfrequency point, operating, respectively, in the ranges 4.0 to 6.0, 6.0 to 8.2, 8.2 to 12.0 GHz. Low-loss cables were used. A network analyzer measured the phase shift and transmission for the reference unit and the snow sample, the output being plotted versus frequency on an X-Y plotter that had separate pens for the phase and transmission channels. Thus, a simple subtraction of one curve from its counterpart (i.e., test minus blank) yielded the data for the snow. A conventional sweep generator was used for the microwave source. To verify that the initial supply of snow was adequately dry, a portion was placed in the test cell and measured. No significant attenuation was obtained. This procedure was followed for each snow supply to verify the initial dry state. Also, the absence of appreciable attenuation at any frequency up to 12 GHz shows that "beam scattering" is negligible in the test cell distance of 14.5 cm.

Impedance mismatch effects at the cell interfaces are negligible. For normal incidence on a medium having dielectric constant k_2 from a medium having dielectric constant k_1, the well-known equations are

$$\left(\frac{\sqrt{k_2} - \sqrt{k_1}}{\sqrt{k_2} + \sqrt{k_1}}\right)^2 = \text{Reflection power}$$

$$\frac{4\sqrt{k_1 k_2}}{\left(\sqrt{k_2} + \sqrt{k_1}\right)^2} = \text{Transmission power}$$

The Plexiglas walls have a dielectric constant of about 2.2. Dry snow of density 0.4 gm/cm^3 has a dielectric constant of 1.8 in the GHz region up to 12 GHz. Wet snow of 6% volume wetness and density of 0.5 gm/cm^3 has a dielectric constant of about 2.8 at 8 GHz. For these values, the greatest loss in transmission would occur if a single step in dielectric constant is assumed, namely, from 1 to 2.8. For such a step, the power transmission is 0.937, representing a loss of 0.28 dB. For interfaces having dielectric constants of 2.2 and 2.8, respectively, the power transmission is 0.996, representing a loss of 0.02 dB. The aggregate effect of the interfaces for the various combinations is less than 1 dB loss; in comparison, the attenuation for wet snow of 6% volume wetness at 8 GHz is 21 dB in 14.5 cm.

Multiple reflections within the test cell under low loss conditions can be identified by the response to swept frequency. When the transmission loss through the 14.5 cm distance exceeds about 5 dB, the effect of multiple reflections becomes small. For most of our measurements, the attenuation in one passage of the test cell exceeded 10 dB at the 8 to 12 GHz range, so multiple reflections represented unimportant perturbations.

MEASUREMENTS

Many exploratory runs were necessary to determine appropriate operating procedure. Our final calibration curves are shown in figures 1-3. The original information was obtained as continuous X-Y curves. A dual-trace (X-YY) plotter gave the frequency as the X axis, the transmitted signal and the phase as two independent ordinates. Successive tracings of the curves were coincident to within the width of the tracing pen. Smooth curves were fitted to the tracings to eliminate obvious (and small) irregularities caused by interfaces. Data "points" were selected at each integral frequency value and are depicted in the figures as X marks.

Figure 1 shows the permittivity for dry snow in the frequency range of 8.2 to 12.0 GHz. The attenuation for the sample, which was 14.5 cm thick in the direction of the beam, was less than 1 dB; it is not plotted.

In figure 2, the permittivity and decibels per centimeter are plotted versus frequency in the range of 8.2 to 12.0 GHz for a snow sample having 2.51 volume percent wetness and density of 0.442 gm/cm^3. Also plotted are the loss factor ε'' and tan δ, which are obtainable from the permittivity and attenuation per centimeter.

In figure 3, for the frequency range of 4.0 to 12.0 GHz, the permittivity, decibels per centimeter, loss factor, and tan δ are shown for a snow sample having 6.24 volume percent and density of 0.558 gm/cm^3.

SNOW WETNESS EQUATIONS

From the measured phase shift (in deg), the permittivity can be calculated (see "symbols"):

$$\varepsilon' = [1 + \phi/12D\nu]^2 \tag{1}$$

The loss factor is obtained from the attenuation and permittivity as follows:

$$\varepsilon'' = \varepsilon' \tan \delta \tag{2}$$

$$\tan^2 \delta + 1 = \left(\left[\frac{\text{dB/cm}}{1.286\nu\sqrt{\xi'}} \right]^2 + 1 \right)^2 \qquad (3)$$

If $\tan \delta << 1$,

$$\tan \delta = \frac{1.0994}{\nu\sqrt{\xi'}} \frac{\text{dB}}{\text{cm}} \qquad (4)$$

Equations (1) through (4) are well known in electromagnetic theory. Curves for various snow samples show the dependence of ξ' and ξ'' on frequency. For convenience, curves are also included for decibels per centimeter and $\tan \delta$, although these evidently are related to ξ' and ξ'' by the preceding equations.

The following three equations are essentially empirical relations. Theoretical considerations served as a guide, but the equations are justified mainly on the basis that they are in agreement with measured values. Analysis of the calibration curves, test runs, and checks for internal consistency resulted in the following relations:

$$\frac{\text{dB}}{\text{cm}} = W_v(0.045[\nu - 4] + 0.066[1 + a]) \qquad (5)$$

$$\xi'_{calc} = 1 + 2\rho + bW_v^{3/2} \qquad (6)$$

and

$$b = 5.87\times10^{-2} - 3.10\times10^{-4}(\nu - 4)^2 \qquad (7)$$

DISCUSSION OF SNOW WETNESS EQUATIONS

Because of its importance, the reliability of equations (5), (6), and (7) is discussed first.

For any snow sample (wetness known by calibration or unknown), the attenuation and phase shift were measured simultaneously by the instrumentation. From the phase shift, the permittivity can be obtained using equation (1). This is the measured value and involves no assumptions.

A calculated value of the permittivity is obtained from equation (6). The data required are the density, wetness, and the value of the parameter b defined in equation (7) as a function of frequency. The wetness can be obtained from calibration data or alternatively from equation (5) with measured attenuation.

Thus, for any snow sample, the measured and calculated values of permittivity can be compared by plotting one value along the X axis and the other along the Y axis. The distribution of such points relative to the 45° line shows how well the two sets of values agree. This is done in figure 4, for 17 samples; some samples were dry, the rest had wetnesses that were obtained from calibration data or from measured attenuation. Various snow densities and grain sizes were included in the samples and various frequencies, in the 4 to 12 GHz range, were used. The excellent agreement of the measured and calculated values of the permittivity provides assurance that equations (5), (6), and (7) are trustworthy.

Equation (5), which gives a semiempirical relation, is now considered. In the frequency range of 4 to 12 GHz, the attenuation per unit length is proportional to the volume-percent wetness and is a linear function of frequency. For convenient reference, equation (5) is plotted in figure 5 for selected frequencies and in figure 6 for selected values of wetness. The value of the constant a is taken to be zero, unless stated otherwise. Equation (5) is based on the data shown in figures 1-3 and is additionally checked by the permittivity comparisons discussed above.

Equation (6), as pointed out earlier, permits a calculation of the permittivity from measurements of the density, attenuation, and frequency. For dry snow, the first two terms in equation (6) yield a value for permittivity that is in close agreement (within a few percent) with the measured permittivity from equation (1), obtained from phase shift in the GHz region. The upper limit to density to be used in equation (1) is 0.6 gm/cm^3. Because the sample dimensions used in these measurements are so large, any crystal orientation effects are presumed to be insignificant because of the randomization produced in the sampling processes. Approximately 50 samples were measured. Our permittivity measurements are about 6% higher than those of Cumming (ref. 1) for snow densities of about 0.2 gm/cm^3, and are in excellent agreement with his densities near 0.5 gm/cm^3.

The third term in equation (6) must be included for the case of wet snow. The factor b is obtained from equation (7) since the frequency is known. The volume-percent wetness for equation (6) can be obtained from calibration data or from equation (5), using measured attenuation per centimeter.

An interesting check on the validity of equations (4) through (7) is obtained by comparing predictions derived from them with the measurements of Cumming (ref. 1). His stated values of wetness, density, and frequency were substituted into the equations of this paper; the results and Cumming's curves are plotted in figure 7. Good agreement is obtained for the density of 0.38 gm/cm^3. For the density of 0.76 gm/cm^3, agreement is evident for the lower portions of the curves, but further investigation is necessary to identify the disparity at the upper portions of the curves.

A comparison of the data of Sweeny and Colbeck (ref. 2) and the equations of this paper is shown in figure 8 for the dielectric constant (or permittivity) and in figure 9 for the loss factor. Because the data of reference 2 include the effect of snow density, three curves are shown in figure 8 for the snow densities, respectively, of 0.5, 0.6, and 0.7 gm/cm^3. Some of the data points of Sweeny and Colbeck agree with the curve for 0.7 gm/cm^3, but most are higher than this curve. According to the equations in this paper, the snow density plays a minor role in regard to the loss factor, and so only the curve for density 0.6 gm/cm^3 is shown in figure 9. The curves for 0.5 and 0.7 gm/cm^3 would essentially coincide with the curve shown. The loss factors of Sweeny and Colbeck are larger than values obtained from our equations.

SNOW DRAINAGE CHARACTERISTICS

The instrumentation measures the wetness of the snow sample without disturbing it in any way because the intensity of the beam is too low to produce measurable melting. The volume-percent wetness versus drain time for three samples is shown in figure 10. Sample A consisted of small grains (0.1 to 0.3 mm diam) and had an initial wetness of about 9.6 volume percent. The wetness was remeasured after drain times totaling 2, 6, and 20 hr. The sample was kept in a 0° C environment at all times. Sample C had large grains (1 mm diam) and an initial wetness of about 9.4 volume percent. Its wetness decreased more rapidly than that of sample A.

Sample B had large grains (1 mm diam) and was treated as follows: (1) the snow was completely immersed in 0° C water for about 10 min then removed and allowed to drain; (2) after 3 hr, it was placed in the test cell and measured; and (3) a second measurement was made at the 18-hr drain time.

Similar data are presented in figure 11. The curves A and C are the same as those shown in figure 10; they are repeated in figure 11 for reference. Curve D shows the drainage characteristic for a sample that initially had a wetness of 6.2 volume percent. Curve E shows that a snow sample having only 4.0 volume-percent wetness did not drain at all, within the measurement capability of the instrumentation, up to a time of 9 hr.

The water speed in "ripe snow" (i.e., grain size approximately 1 mm diam) was measured with sample C. After the drain time of 20 hr, a 3-cm-deep region was present at the bottom of the snow cell (where it did not produce beam attenuation); the region had a wetness of about 33 volume percent and the appearance of "slush." The snow cell was inverted to bring the slush layer above the beam axis; this caused the accumulated water to drain down through a distance of about 21 cm to the beam region. Based on the time for maximum beam attenuation to occur, the measured speed of travel of the pulse of water for the stated conditions was about 20 cm/min. Further measurements of water passage under a variety of conditions are planned.

APPLICATIONS OF TECHNIQUE

The techniques discussed here may have many applications. We plan to measure the permittivity and attenuation of a variety of snow samples that differ in density, grain size, wetness, age, etc. Those measurements will be made to confirm and to extend the data base. After an adequate number of samples is available, the technique can be used for "snow truth;" that is, from the electrical measurements of samples one can determine the physical characteristics of the snowpack.

The equations presented here permit the rapid determination of snow wetness in the field by measurement of the attenuation of samples. Since phase measurements are not required, the instrumentation can be quite simple and inexpensive, such as a system having microwave horns, an oscillator that can be swept in frequency, and a detector. Details will be published in a later paper.

An important application is the prediction of the time and rate of snow melt for reservoir management in the western United States. Sets of microwave horns located at snow courses can provide data on a daily basis to assess the wetness of the snowpack. Several pairs of horns located at different heights above Earth and immersed in the snow can indicate the liquid-phase content. The instrumentation may be capable of predicting when the snowpack will reach its maximum water-holding state and thus be primed for runoff. Another potential application, although somewhat speculative at present, is the measurement of snowpack wetness for avalanche warning.

The techniques can be employed to measure water speed in snow, earth, and similar materials by observing the changes in attenuation caused by wetness. A version of the technique may permit the in situ measurement of soil moisture on a repetitive basis, to provide index-station data.

SUMMARY OF RESULTS AND CONCLUSIONS

Samples of natural snow have been calibrated by the addition of known amounts of water, thoroughly mixed, and measured in large-volume cells. The phase shift and the attenuation were measured in the frequency range of 4 to 12 GHz. Density was obtained for each snow sample.

Empirical equations were developed from the data, giving the relation between attenuation per unit length and volume-percent wetness. Additional equations were developed for the calculation of permittivity from snow density, attenuation per unit length, and frequency. A comparison showed excellent agreement between the permittivity obtained from phase-shift measurement and that calculated from the equations.

The water passage in snow having a typical grain diameter of 1 mm was measured and found to be about 20 cm/min. Curves are given to show the dependence of snow wetness on drain time for a variety of samples.

It is concluded that "ripe snow" (grain diameter of about 1 mm) can hold about 0.04 g of liquid-phase water per cubic centimeter of snow, equivalent to about 8 weight percent for snow whose density is 0.5 gm/cm^3. This represents the 24-hr drain time state, based on homogeneous samples. The presence of layers, ice lenses, and similar impediments to the flow of water may produce increased snow wetness.

SYMBOLS

ν	frequency, GHz, equal to 10^9 Hz
ξ'	permittivity, real part of dielectric constant relative to vacuum
ξ''	loss factor, imaginary part of dielectric constant relative to vacuum
$\tan \delta$	ratio of imaginary/real parts of dielectric constant
ϕ	phase shift, deg
ρ	density, gm/cm^3
D	thickness of sample, cm
a	average snow grain diameter (in mm) for the range of 0.1 to 1.0 mm
b	proportionality constant
W_v	wetness in volume percent, grams of water per cubic centimeter multiplied by 100
W_w	wetness in weight percent, grams of water per gram of snow multiplied by 100

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FIGURE CAPTIONS

FIG. 1. Calibration curve for dry snow.

FIG. 2. Calibration curves for wet snow (2.51 volume percent).

FIG. 3. Calibration curves for wet snow (6.24 volume percent).

FIG. 4. Comparison of measured and calculated permittivities.

FIG. 5. Variation of attenuation with snow wetness at selected frequencies.

FIG. 6. Variation of attenuation with frequency at selected snow wetnesses.

FIG. 7. Comparison of Cumming's results (tan δ vs snow wetness) with corresponding results of present paper.

FIG. 8. Comparison of Sweeny and Colbeck's results, permittivity vs wetness, with corresponding results of present paper.

FIG. 9. Comparison of Sweeny and Colbeck's results, loss factor vs wetness, with corresponding results of present paper.

FIG. 10. Variation of snow wetness with drain time for initially saturated snow.

FIG. 11. Variation of snow wetness with drain time for different degrees of initial wetness.

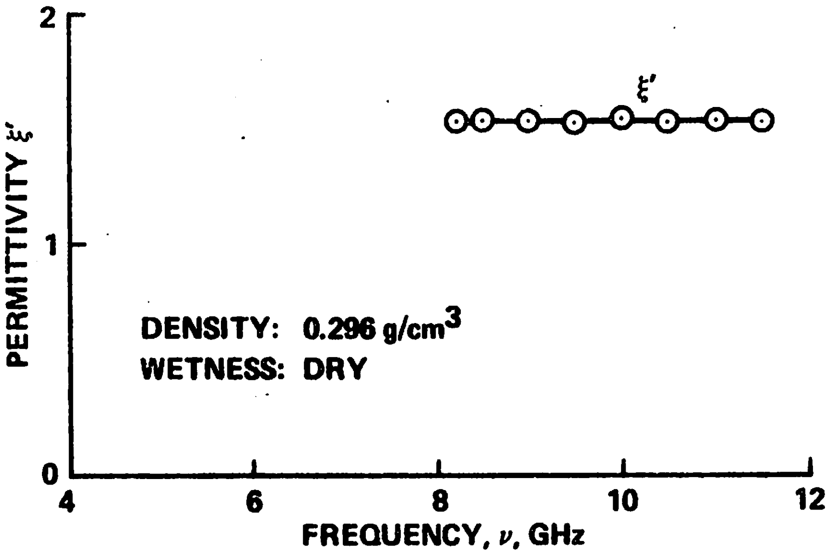
2
1
0
PERMITTIVITY ξ′
ξ′
DENSITY: 0.296 g/cm³
WETNESS: DRY
4
6
8
10
12
FREQUENCY, ν, GHz

Figure 1

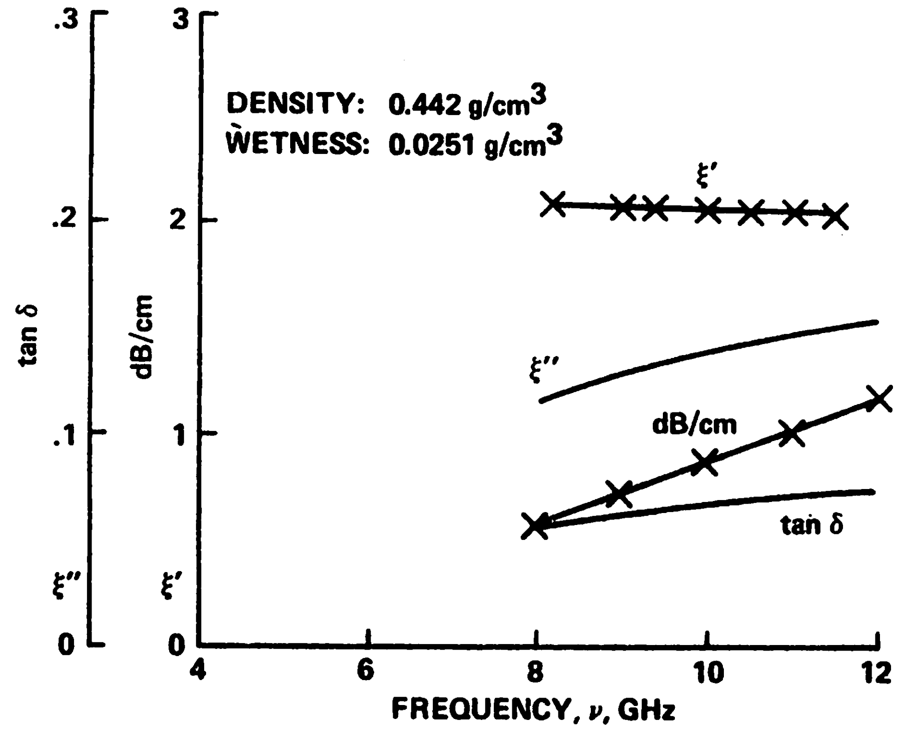
DENSITY: 0.442 g/cm3
WETNESS: 0.0251 g/cm3
ξ'
ξ''
dB/cm
tan δ
.3
.2
.1
0
3
2
1
0
ξ''
ξ'
tan δ
dB/cm
4
6
8
10
12
FREQUENCY, ν, GHz

Figure 2

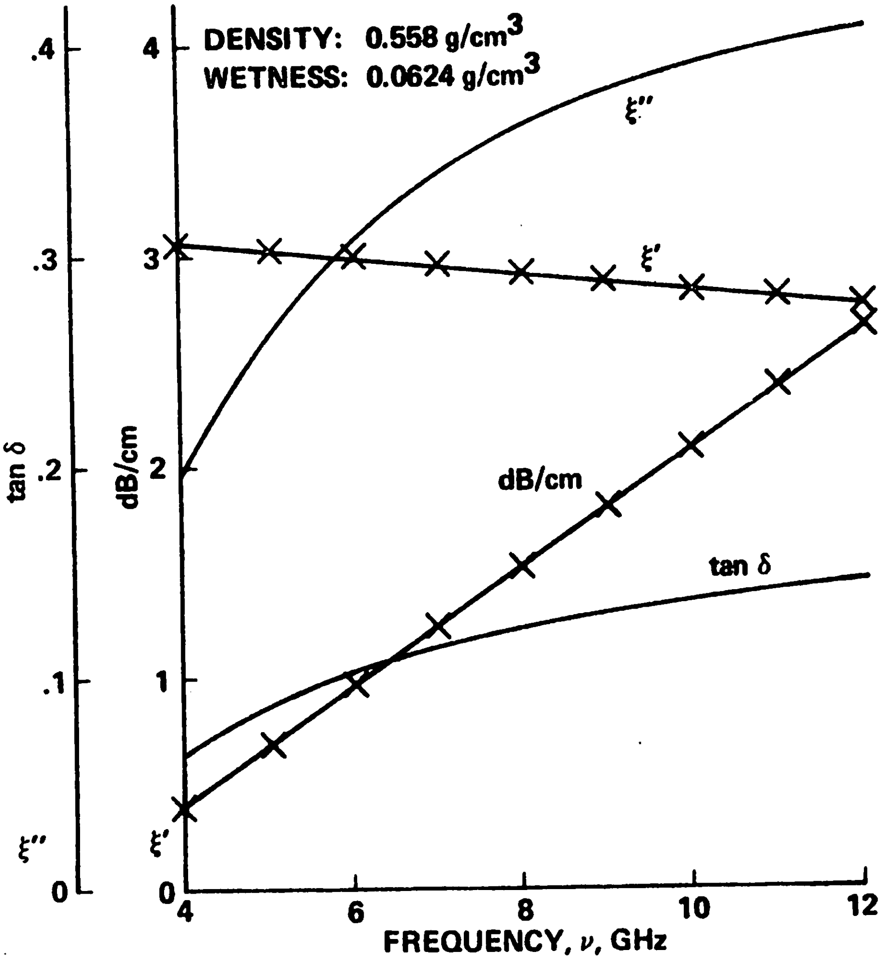
DENSITY: 0.558 g/cm^3
WETNESS: 0.0624 g/cm^3
ξ''
ξ'
dB/cm
tan δ
tan δ
dB/cm
ξ''
ξ'
.4
.3
.2
.1
0
4
3
2
1
0
4
6
8
10
12
FREQUENCY, ν, GHz

Figure 3

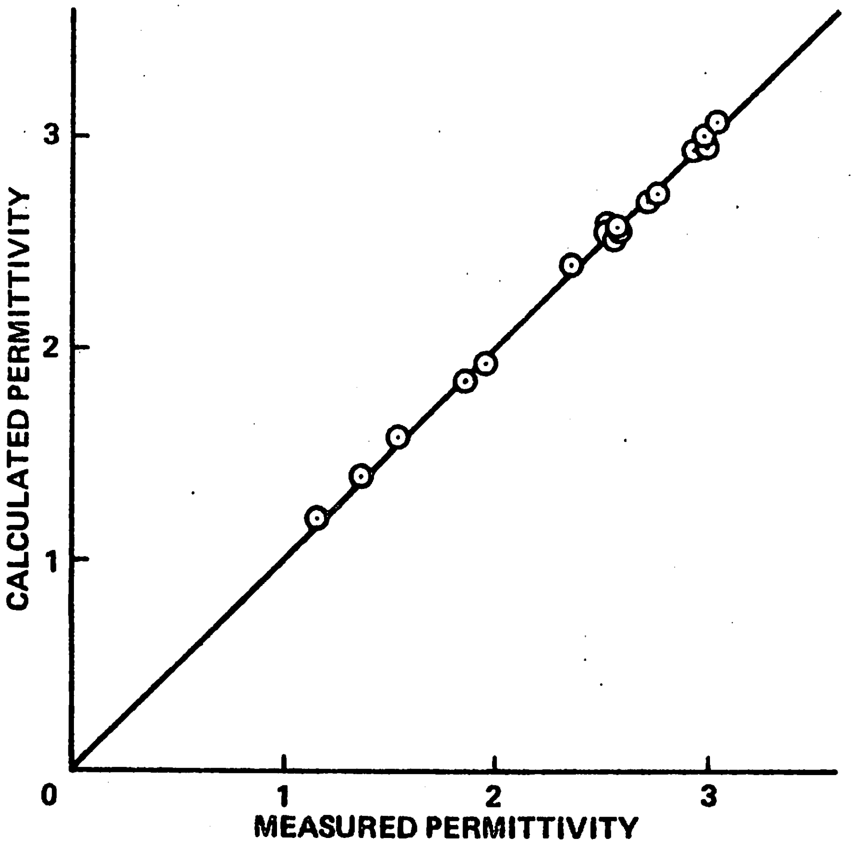

Figure 4

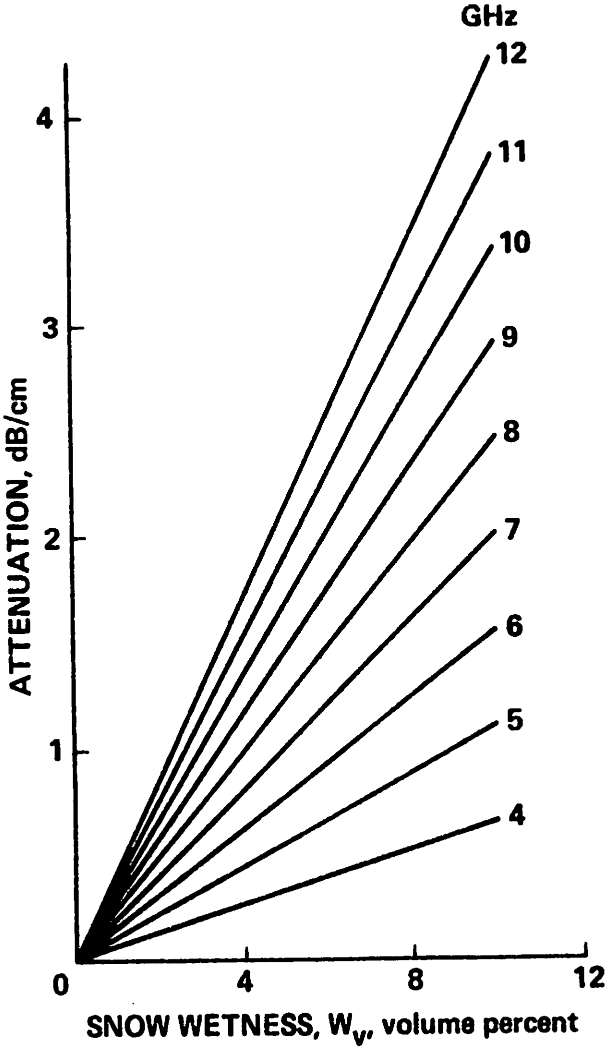
GHz
12
11
10
9
8
7
6
5
4
ATTENUATION, dB/cm
0
1
2
3
4
0
4
8
12
SNOW WETNESS, W_v, volume percent

Figure 5

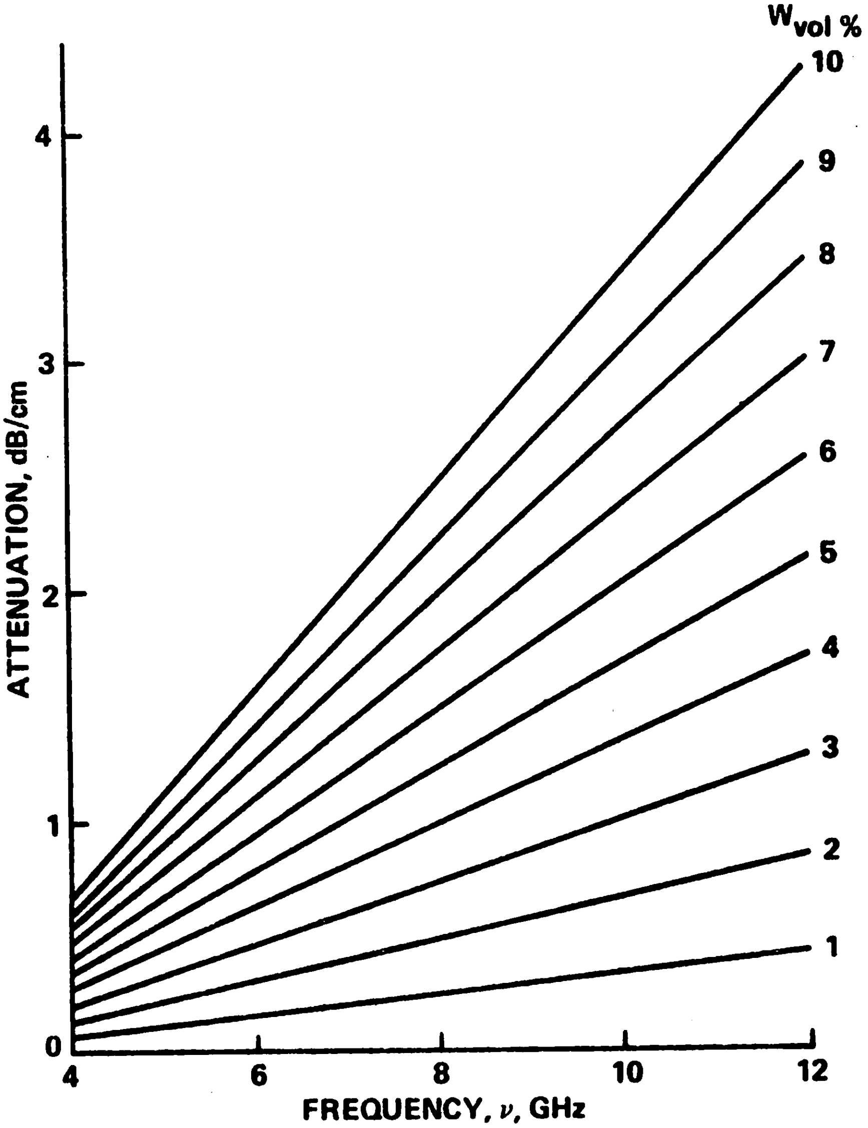
W_{vol} %
10
9
8
7
6
5
4
3
2
1
ATTENUATION, dB/cm
0
1
2
3
4
4
6
8
10
12
FREQUENCY, ν, GHz

Figure 6

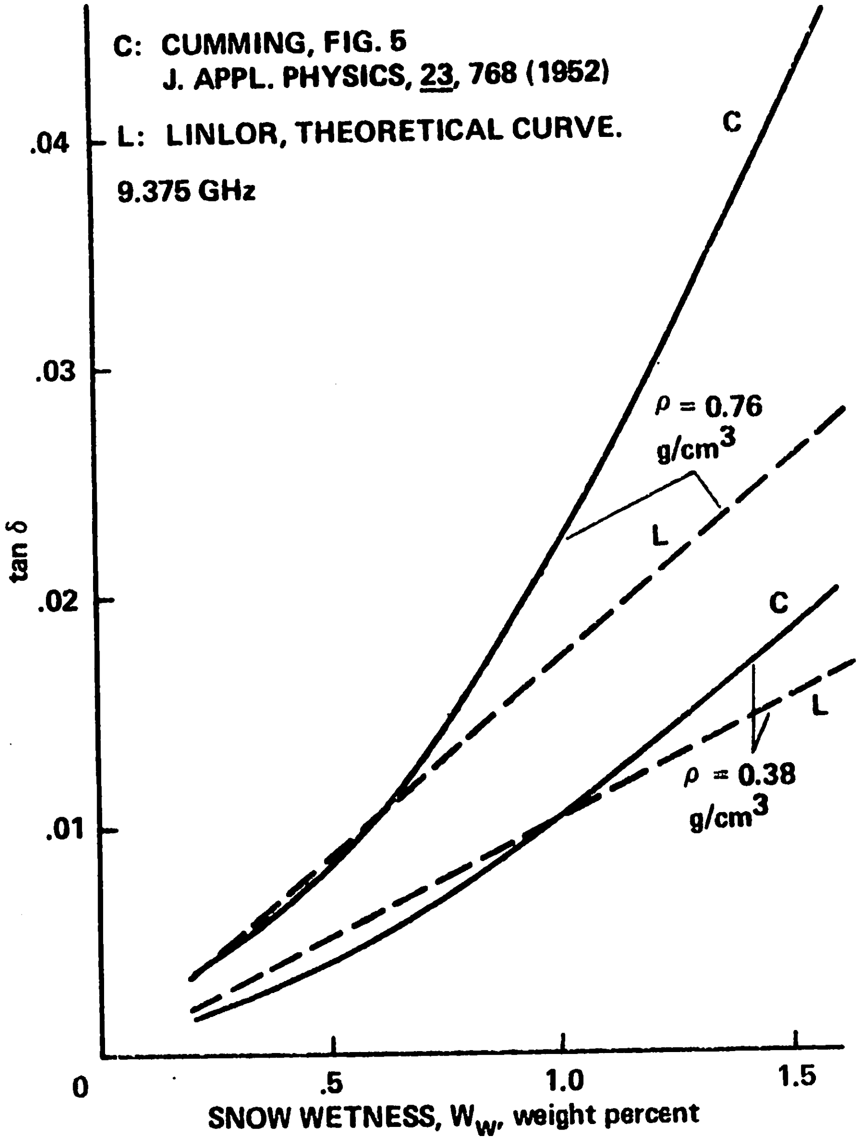
C: CUMMING, FIG. 5
J. APPL. PHYSICS, 23, 768 (1952)
L: LINLOR, THEORETICAL CURVE.
9.375 GHz
.04
.03
.02
.01
0
tan δ
C
ρ = 0.76 g/cm^3
L
C
L
ρ = 0.38 g/cm^3
.5
1.0
1.5
SNOW WETNESS, W_w, weight percent

Figure 7

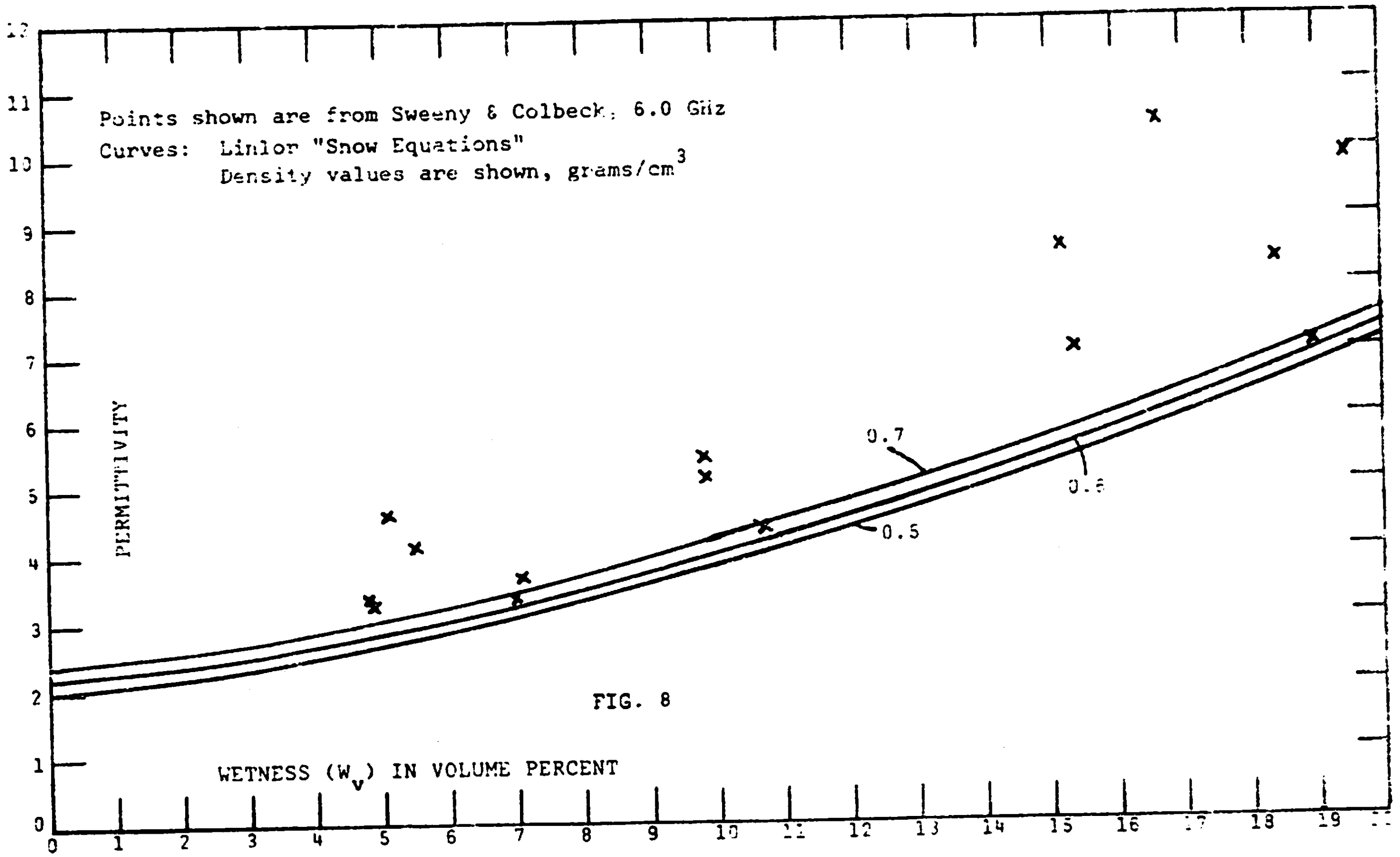

FIG. 8

Figure 6

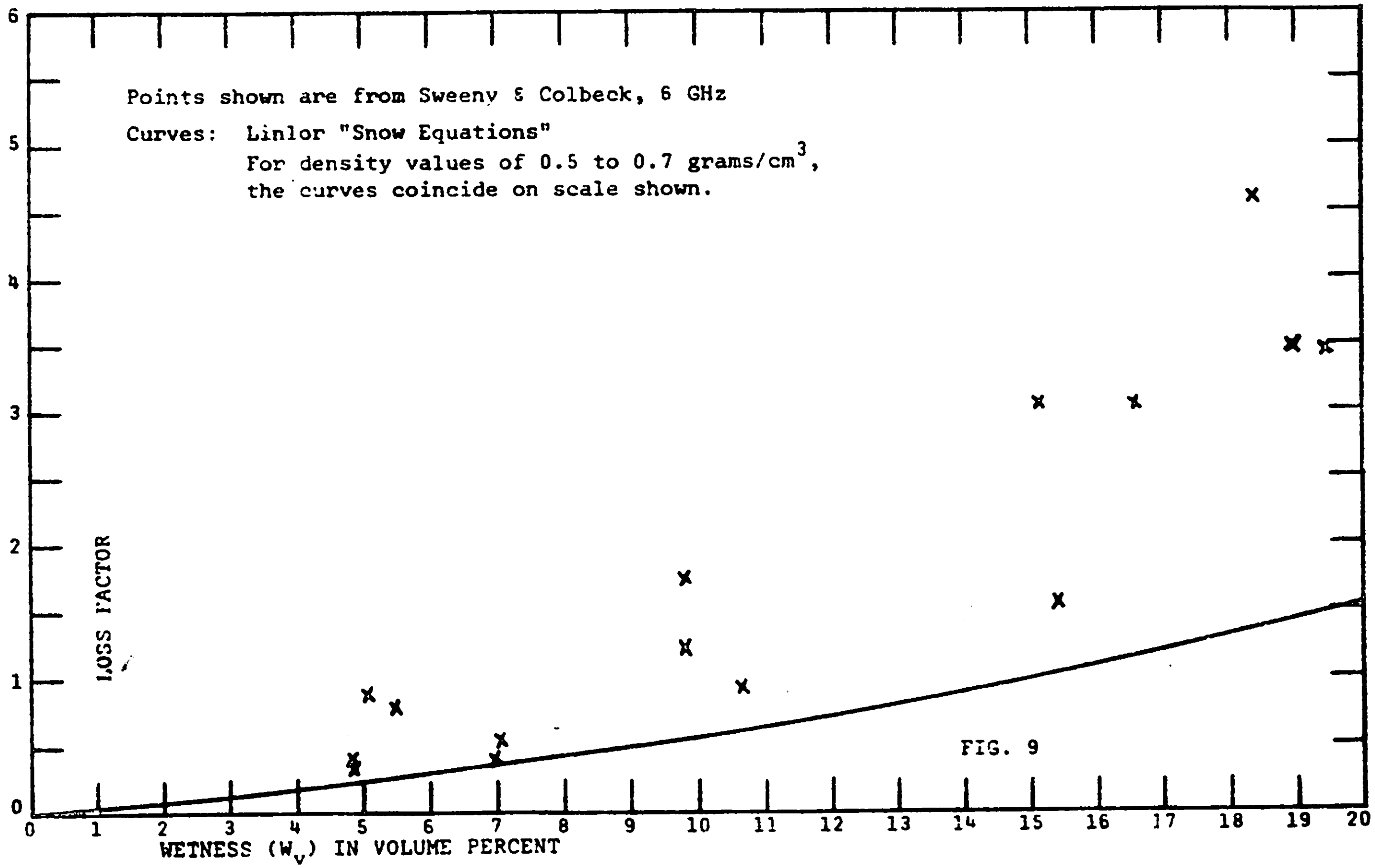
Points shown are from Sweeny & Colbeck, 6 GHz
Curves: Linlor "Snow Equations"
For density values of 0.5 to 0.7 grams/cm^3, the curves coincide on scale shown.
LOSS FACTOR
0
1
2
3
4
5
6
WETNESS (W_v) IN VOLUME PERCENT
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
FIG. 9

Figure 9

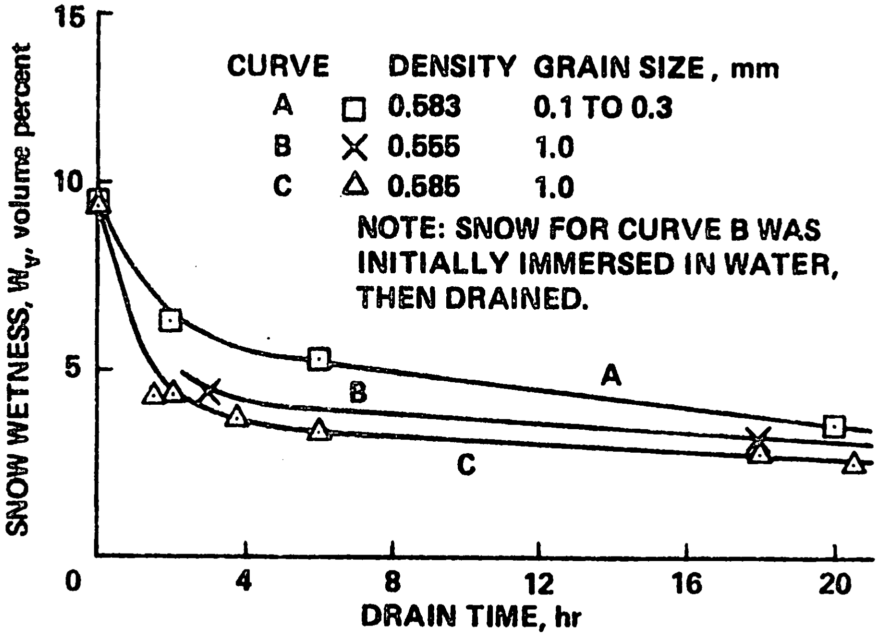
15
10
5
0
4
8
12
16
20
SNOW WETNESS, W_v, volume percent
DRAIN TIME, hr
CURVE DENSITY GRAIN SIZE, mm
A □ 0.583 0.1 TO 0.3
B X 0.555 1.0
C △ 0.585 1.0
NOTE: SNOW FOR CURVE B WAS INITIALLY IMMERSED IN WATER, THEN DRAINED.
A
B
C

Figure 10

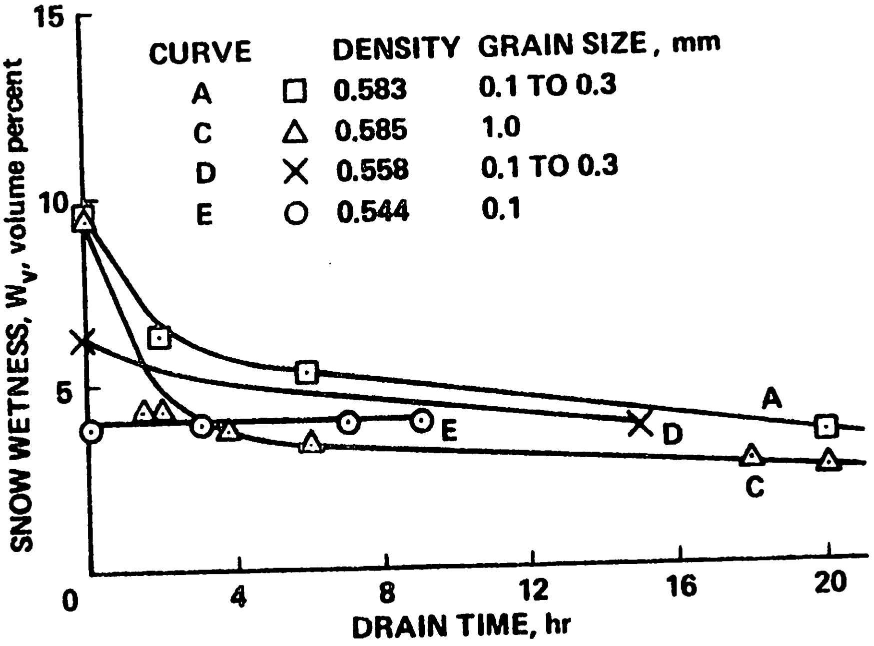
15
10
5
0
CURVE
DENSITY
GRAIN SIZE, mm
A □ 0.583 0.1 TO 0.3
C △ 0.585 1.0
D ✕ 0.558 0.1 TO 0.3
E ○ 0.544 0.1
SNOW WETNESS, W_v, volume percent
A
D
E
C
4
8
12
16
20
DRAIN TIME, hr

Figure 11