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Icing and Snow Accretion on Electric Wires

by

Daisuke Kuroiwa

U.S. ARMY MATERIEL COMMAND
COLD REGIONS RESEARCH & ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

PREFACE

This report was prepared by Dr. Daisuke Kuroiwa for the Materials Research Branch, Research Division, James A. Bender, Chief.

This brief review was written with the objective of providing useful experimental data on icing and snow accretion on electric wires and antennas for microwave engineers. Almost all data were collected during investigations in Japan.

This report has been reviewed and approved for publication by the Commander, U. S. Army Materiel Command.

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Experimental data on icing and snow accretion on electric wires and antennas is presented. The accumulation of supercooled droplets on a single wire stretched in an air flow has been calculated as icing in the form of soft rime, hard rime, and glaze, per unit time and unit length of wire. The difference between calculated values and observed values in Japan is discussed in terms of ice deposit, wire tension, and wind velocity and pressure. Iced wire will be cut more often by dynamic wind pressure than by the deposited ice load. The differences between icing and accretion of snow are discussed, the wire failures being attributed to the heavy weight of snow accretion. This phenomenon will be less frequent in polar regions than in temperate regions because the main cause of snow accretion—existence of liquid-water film on the surface of snow flakes—is less prevalent. A simple experiment for anti-icing an electric wire by means of electrical heating is briefly described.

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Introduction

Icing and snow accretion are similar in appearance, but there are great differences in the meteorological conditions during which the phenomena take place. Icing is a result of the repeated impingement and freezing of fog particles carried one after another to an object by wind. Therefore, liquid-water droplets, supercooled below 0°C in the atmosphere, and strong winds are necessary. Snow accretion is a result of the accumulation of wet snow near the air temperature 0°C. The existence of snowflakes and weak wind is required for its occurrence.

Types of icing

Three types of icing are observed in the natural atmosphere: soft rime, hard rime, and glaze.

Soft rime is observed most frequently in mountain districts. Figure 1a shows a sketch of soft rime deposited on a cylinder. It looks like a "shrimp's tail", because it attaches to a small point on the surface of the cylinder and grows triangularly windward. It is white and opaque. A granular structure is observed under a microscope (Fig. 1b). The density of soft rime is less than 0.6 g/cm^3, and its adhesive force to wire is not strong. It can be removed easily by slight shock.

Figure 2a is a sketch of typical hard rime deposited on a cylinder. Icing of this type consists of a hard ice block, transparent or opaque. Sometimes it is called "clear ice". Microscopic observation (Fig. 2b) shows a layered structure in which transparent (clear) ice and opaque ice (containing many air bubbles) alternate. Hard rime does not show granular structure like soft rime, and its density ranges between 0.6 and 0.9 g/cm^3. Its adhesion to wire is so strong that shock may not remove it.

Glaze is a transparent ice deposit, which is sometimes called "blue ice" (Fig. 3). The surface of glaze is smooth, and unfrozen water drops blown out from the windward sides are frozen at the lee sides of the cylinder. The density of glaze is the same as pure ice, 0.9 to 0.92, and its adhesive force is strong.

Relationship between the three types of icing and meteorological conditions

The type of icing is determined by combinations of the following meteorological factors: air temperature, wind velocity, diameter of supercooled droplets, and liquid water content in unit volume of air. Figure 4a shows the relation of the three types of icing to air temperature and the size of supercooled water droplets; Figure 4b shows their occurrence as a function of air temperature and wind velocity. These data were taken from observations at Mt. Fuji (altitude 3776 m) and Mt. Neseko (altitude 1300 m) in Japan. Glaze is observed where the air temperature and wind velocity are high and the diameter of water droplets is large; rime is observed where the air temperature and wind velocity are low and the diameter of water droplets is small (Fig. 4). When a supercooled water droplet impinges on a wire, freezing begins from the surface of contact, but is not instantaneously completed. The time required for complete freezing depends on the rate of transfer of latent heat from the freezing of water droplets. If the impingement of water droplets takes place continuously before the supercooled water droplets have completed freezing, the icing will grow with the surface covered with a water film. This process is called "wet growth". In this case, icing takes the form of glaze. On the contrary, if a supercooled water droplet impinges and freezes on a frozen droplet, icing will grow with a dry surface. This is "dry growth", in which icing develops into white soft rime with many air voids. The criteria for formation of these three types of icing can be described as follows, where τ is the time required for complete freezing of supercooled water droplets and ε is the time interval of impingement of supercooled water droplets:

$\tau < \varepsilon$ = dry growth, soft rime.

This condition is satisfied when the air temperature and wind velocity are low, and the diameter of supercooled water droplets is small.

$\tau > \varepsilon$ = wet growth, glaze.

This condition is satisfied when the air temperature and wind velocity are high, and the diameter of supercooled water droplets is large.

$\tau \approx \varepsilon$ = hard rime.

This condition is between soft rime and glaze (Fig. 4).

Accumulation of supercooled water droplets on a single wire stretched in the air flow

In order to study the prevention of icing on a wire or antenna, it is important to know how much icing takes place per unit time and per unit length of wire. We shall consider the rate of ice deposit of each icing type.

Growth rate of glaze. Glaze grows under the condition that $\tau > \varepsilon$. In this case, impinged water droplets cannot freeze unless the latent heat is transferred into the air by convection or evaporation. If we assume that the whole surface of the cylinder is covered with a water film kept at 0°C, the growth rate of glaze per unit length of cylinder is given by

$$\frac{dM}{dt} = 1.05 \times 10^{-5} \sqrt{VR}\,\theta \tag{1}$$

where M is ice mass, V the wind velocity, R the radius of the cylinder, and θ the air temperature (negative). When the icing reaches a certain length toward the wind, the wire twists because of the heavy weight of the icing (Fig. 5). Thus, the icing on a wire gradually develops the form of a cylinder, and its radius R increases with time. The growth rate of the radius of icing on a wire is given by integration of eq 1.

$$R^{\frac{3}{2}} = 2.3 \times 10^{-6} \sqrt{V}\ \theta t \tag{2}$$

where the density of glaze was taken as 0.9 g/cm³. In Figure 6, the growth curves of glaze deposited on wire are given as a function of time, air temperature and wind velocity.

Growth rate of soft and hard rime. Soft rime and hard rime are formed under the condition $\tau \leqq \varepsilon$. In this case, there arises the important problem of how many water droplets are captured by wire. We shall consider the collection efficiency of a cylinder for supercooled water droplets. Figure 7 shows a typical ice deposit on a cylinder placed in the air flow. The axis of the cylinder is perpendicular to the air stream. If the diameter of the supercooled water droplets is very small, they can flow with the air around the cylinder and do not form any ice deposit on the cylinder. However, as water droplets begin to have larger diameters, they gather momentum and deviate from the air stream, impinging on the surface of the cylinder and forming an ice deposit a-b-c-d (Fig. 7). The amount of ice deposited per unit time and length of cylinder is given, in general, by

$$\frac{dM}{dt} = 2ERVw \tag{3}$$

where dM denotes the mass of supercooled water droplets which give rise to icing for time dt, R denotes the radius of the cylinder, V the wind velocity, and w the liquid-water content. E is the so-called "collection efficiency" and has a value between 0 and 1. According to Langmuir (1946), E is given by the following two dimensionless factors:

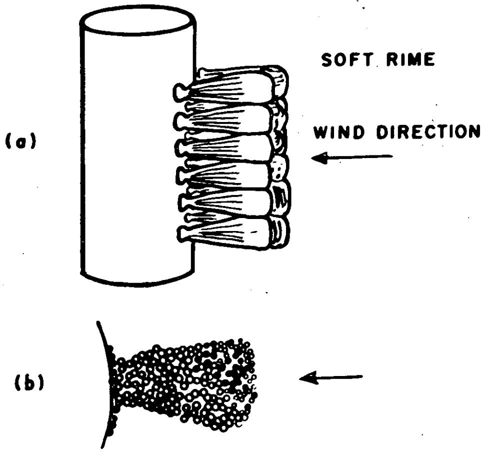

Figure 1. Soft rime.

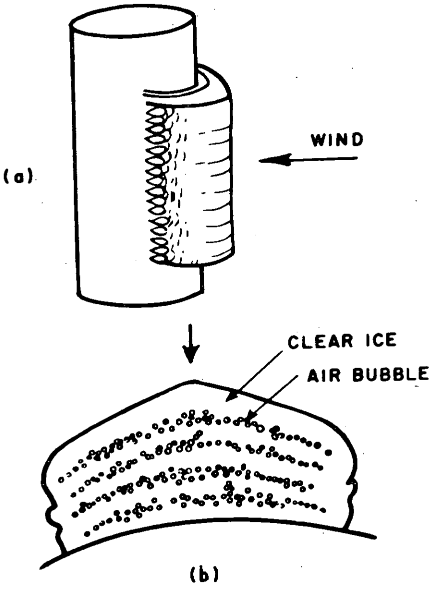

Figure 2. Hard rime.

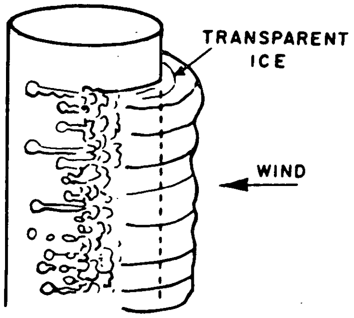

Figure 3. Glaze.

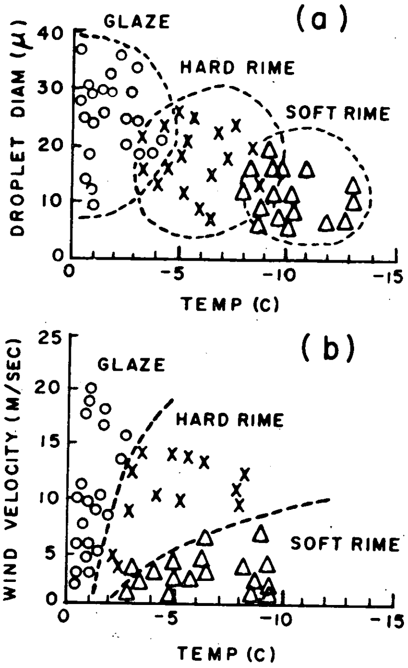

Figure 4. Relation between types of icing and meteorological conditions.

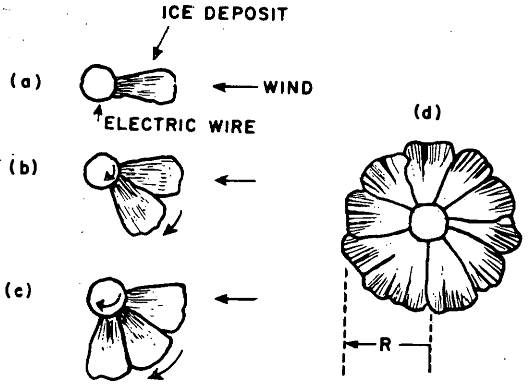

Figure 5. Growth process of icing on wires.

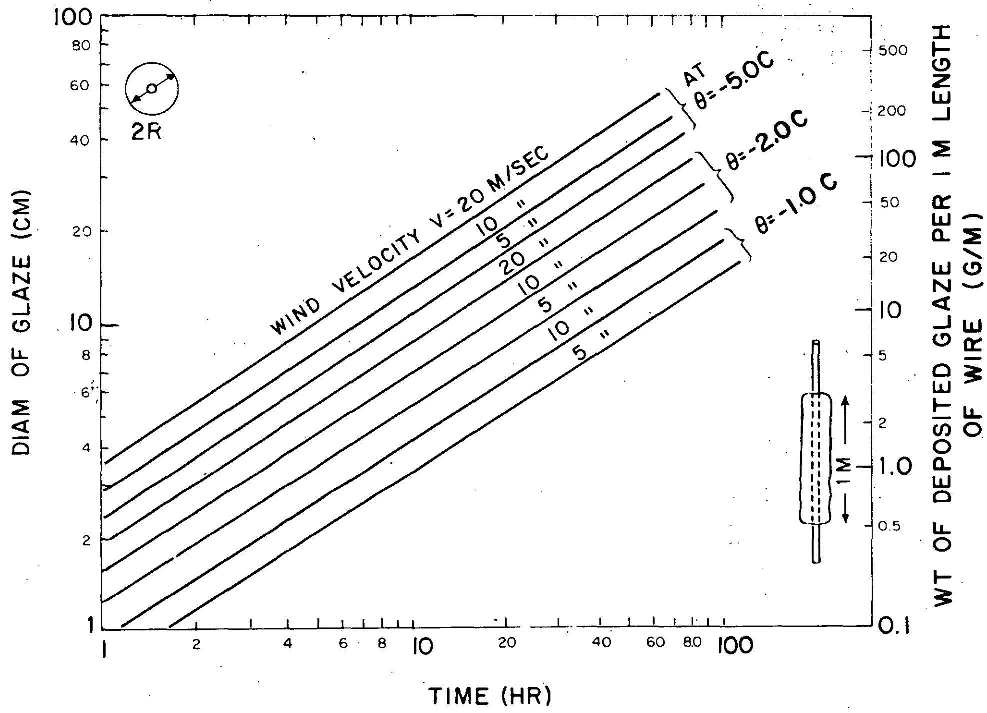

Figure 6. Growth curve of glaze deposited on a wire (Imai, 1953).

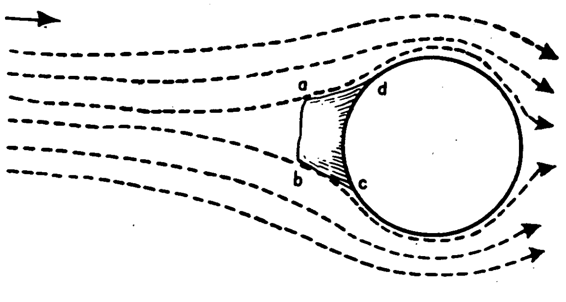

Figure 7. Ice deposit on a cylinder.

$$E = f(K, \phi), \qquad K = 1.29 \times 10^3 \frac{V r^2}{R}, \qquad \phi = 0.162\ VR,$$

where r = radius of droplet. Figure 8 shows the collection efficiency of a cylinder as a function of K and ϕ. If $K \leq \frac{1}{8}$, E equals 0 for any value of ϕ. If the wind velocity and the size of a water droplet are given, it then becomes possible to find the limit of cylinder radius beyond which icing does not take place. Denoting the radius at this limit by R_c:

$$R_c = 1.03 \times 10^4 V r^2. \tag{4}$$

Figure 9 illustrates the critical radius, R_C, as a function of wind velocity and the radius of the droplet. For $r = 2\,\mu$, $V = 10$ m/s, for instance, icing does not occur on a cylinder having a diameter above 1 cm. This calculation, however, is purely theoretical; in actual cases, some icing still takes place because the air flow is turbulent. If a cylindrical deposit of soft or hard rime is formed on wire as shown in Figure 5, the time required for the radius of the deposited ice to increase from R_1 to R_2 is given by integration of eq 3 as follows:

$$t = \frac{\pi \rho}{Vw} \int_{R_1}^{R_2} \frac{dR}{E}. \tag{5}$$

Figure 10 shows the calculated growth curves of rime as a function of the liquid-water content, wind velocity, and radius of the droplet, assuming the density of rime as 0.6 g/cm^3.

Observation of icing on an electric wire at Mt. Neseko

In the previous section the problem of icing on wire is treated from a theoretical point of view. In general, there are great differences between calculated values and observed data because of the complexity and changeability of meteorological conditions. Observations of wire icing were carried out on Mt. Niseko (Hokkaido, Japan) in 1944. Aluminum wires and copper wires, each with diameters of 2.9 mm and 2.0 mm, were stretched 20 m perpendicular to the wind direction. The ends of the wires were connected to a tension meter. Strong icing (hard rime) took place on 20 March 1944. The air temperature was -6 to -11C; wind velocity was 5 to 15 m/sec. Figure 11a shows the growth of the diameter of hard rime deposited on an aluminum wire (2.9 mm diam) and the increase in weight of the ice deposit per centimeter length of wire. Figure 11b represents the increase of the total tension of the wire and the weight increase of hard rime covering the whole length of the stretched wire. The tension meter recorded both

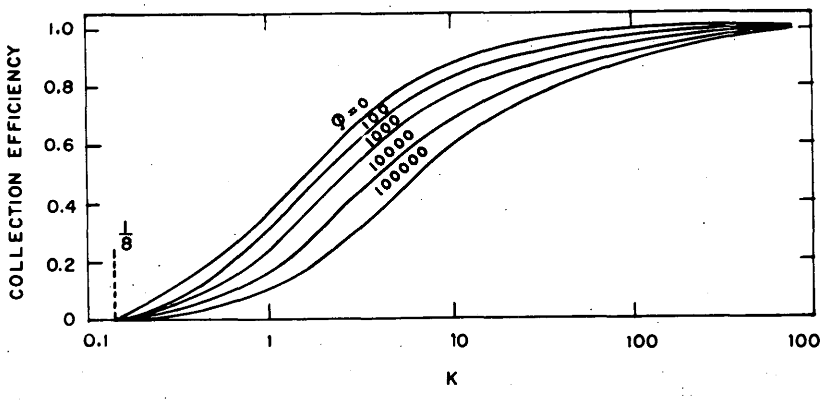

Figure 8. Collection efficiency of a cylinder.
(Langmuir & Blodgett, 1946)

the total weight of the deposited ice and the dynamic pressure of wind. Therefore, subtracting the bottom curve from the top one gives some information about the dynamic pressure of wind on an iced wire. Figure 12 shows the relation between wind-velocity variation and tension from wind pressure. This curve suggests that iced wire will be cut more often by dynamic pressure of wind than by total weight of deposited ice. Figures 13a and b show data observed on 21 March 1944. The air temperature was -5C to -10C, wind velocity was 20 m/sec, and strong icing lasted over 20 hours. In this case, all electric wires were cut by strong wind. The following table gives the total weights and diameters of deposited ice immediately after the electric wires were cut:

		Total weight of deposit	Diameter of deposit
Aluminum wire	2.0 mm	about 35 kg	about 6 - 7 cm
	2.9 mm	55 kg	8 - 9 cm
Copper wire	2.0 mm	55 kg	8 - 9 cm
	2.9 mm	110 kg	11 - 12 cm

A simple experiment for anti-icing an electric wire

A test for anti-icing an electric wire by means of electrical heating was carried out at Mt. Niseko. A small nickel-chromium wire 7 m long with a diameter of 0.68 mm was stretched perpendicular to the air stream. An electric current was supplied through the wire to keep its surface temperature at 0°C under any meteorological conditions, and the minimum electric current required for anti-icing was observed.

According to the theory of heat transfer, the convective heat loss from the surface of the electric wire into the air stream is

$$q = c \sqrt{VR}\ \theta \tag{6}$$

where q is heat loss per unit length of wire, V is wind velocity, R is radius of wire, θ is the temperature difference between the surface of the wire and air flow, and c is the coefficient of heat transfer. The critical heat required to keep the surface of the wire completely free from icing can easily be calculated from the observed electric current. A relation between the ratio $q/\sqrt{VR}$ and the temperature difference θ is plotted in Figure 14a. If the coefficient of heat transfer is kept constant, the curve must be expressed by a straight line, but actual observed data deviate from the linear relation. A dotted line illustrates Russel's experimental data, $c = 4 \times 10^{-4}$ cal/cm-sec-C (see Eason, 1930). The deviation from this line means an additional heat loss due to evaporation of water droplets from the surface of the heated wire. Figure 14b shows the effective heat required for complete anti-icing as a function of wind velocity and air temperature. The curves are equal-heat-quantity lines for complete prevention of icing. For example, 0.06 cal/cm^2-sec will prevent icing at θ = -5C and V = 5 m/sec.

Snow accretion

Snow accretion on wire looks like icing on wire but there are great differences in meteorological conditions under which it takes place. Snow accretion is a result of the accumulation of snowflakes on wire. There is no need for supercooled water droplets in the atmosphere. Figure 15 shows the meteorological conditions for the occurrence of snow accretion observed in Japan during three winters from 1949 to 1952. Snow-accretion data were plotted only for snow-precipitation rates greater than 0.1 g/cm^2-hr. According to this figure, almost all snow accretions are observed when the wind velocity is less than 3 m/sec and air temperature is -1 to +1C. In such conditions, the accumulated snow is held stably around a wire because of stickiness due to the liquid water contained in it. Successive stages of snow accretion are shown schematically in Figure 16. When snow deposited on the wire reaches a certain thickness, the snow rotates gradually around the wire forming a "snow ribbon". The snow ribbon does not fall from the wire unless a strong wind blows it away. Continued snowfall makes a massive cylindrical snow accretion. The main cause of snow accretion on the electric wire is the existence of a liquid-water film on the surface of snow flakes. Therefore, it is believed that this phenomenon will be less frequent in polar regions than in temperate regions.

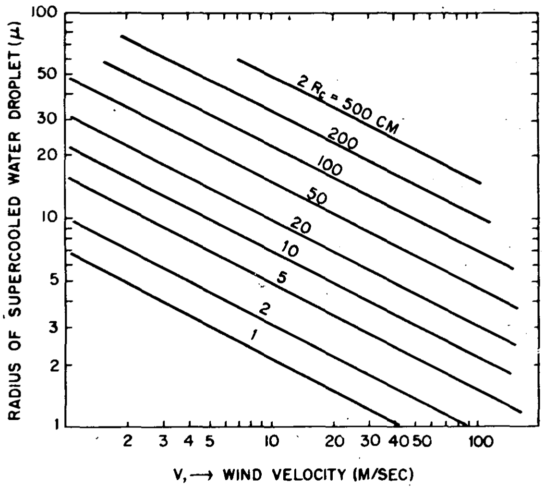

Figure 9. Critical radius of cylinder above which icing does not take place. (Imai, 1953)

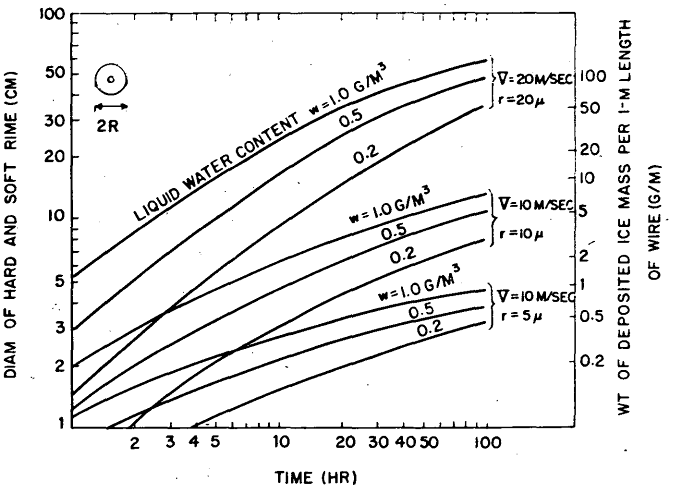

Figure 10: Growth curve of hard or soft rime deposited on a wire. Density = 0.6 g/cm³. (Imai, 1953)

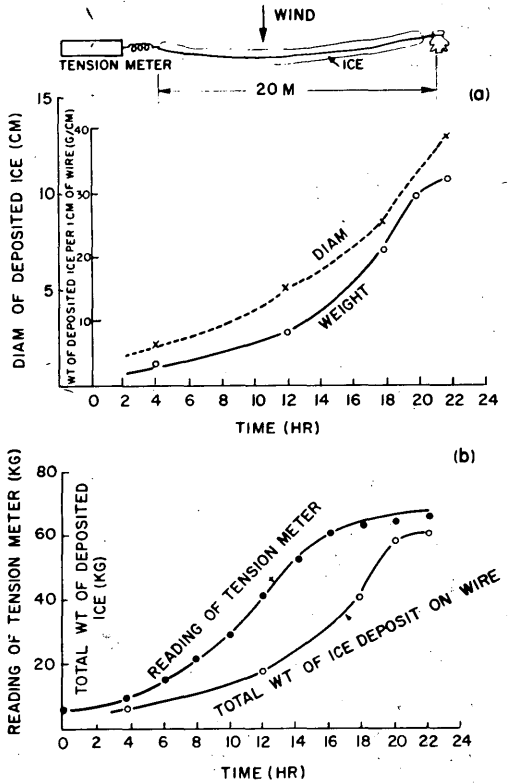

Figure 11. Observed accretion of icing on a wire. Wind 5 to 15 m/s. Air temp -6 to -11C. (Oguchi, 1953)

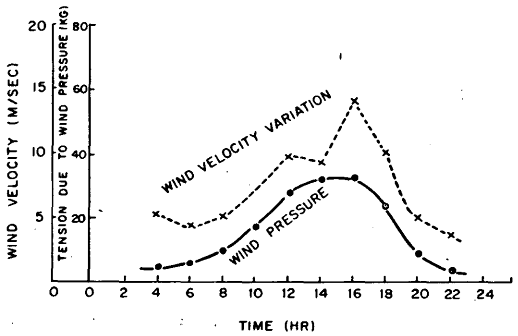

Figure 12. Relation between wind velocity and wind pressure loaded on the iced-wire. (Oguchi, 1953)

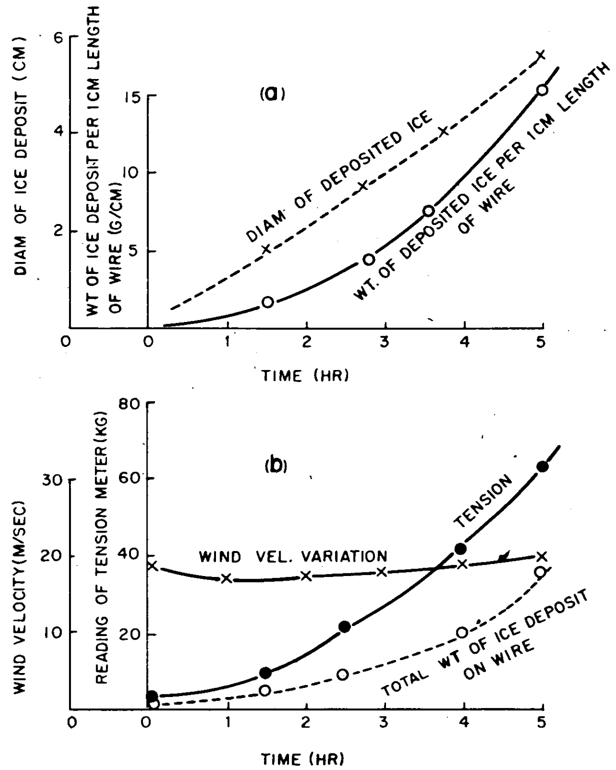

Figure 13. Observed accretion of icing on a wire, 21 March 1944. Air temp -5 to -10C. (Oguchi, 1953)

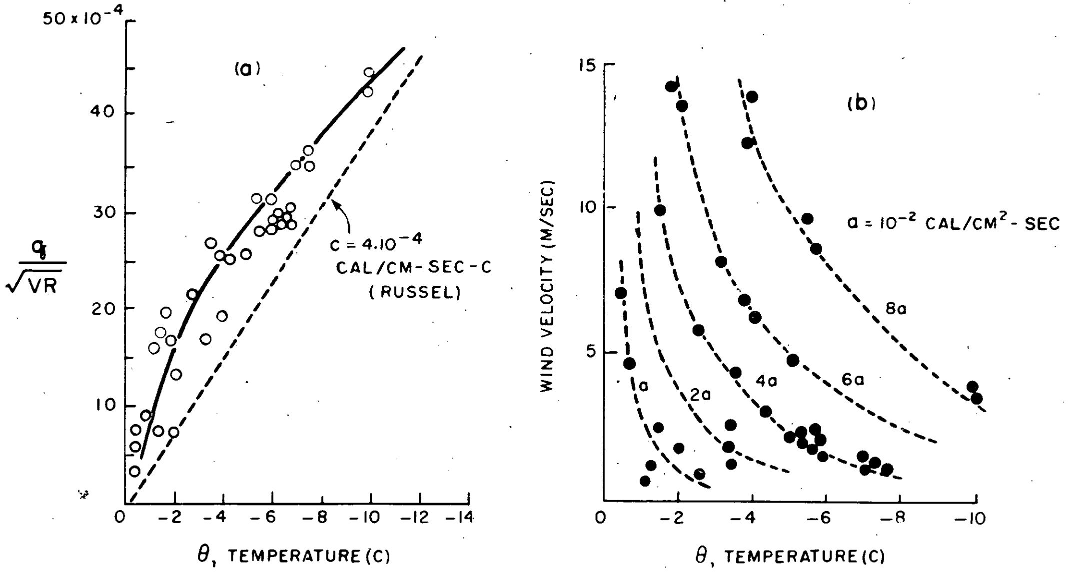

Figure 14. Relations between $q/\sqrt{VR}$ and air temperature (Oguchi, 1953). Wire temperature maintained at 0°C. Dotted line in (a) is from Russel's experimental data. (see Eason, 1930)

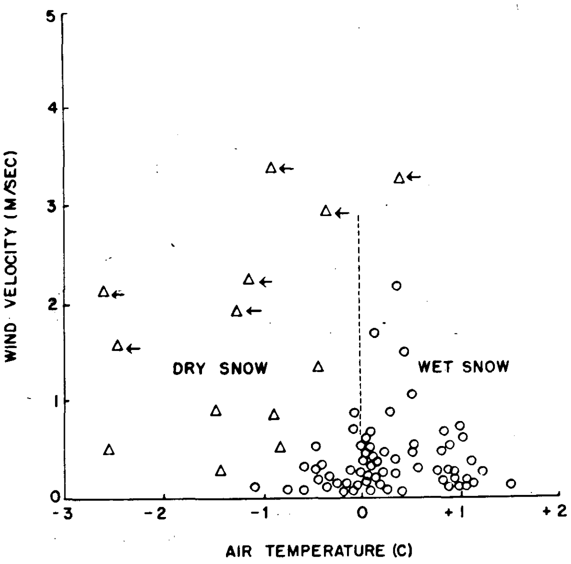

Figure 15. Meteorological conditions for snow accretion on wire, 1949-52. (Shoda, 1953)

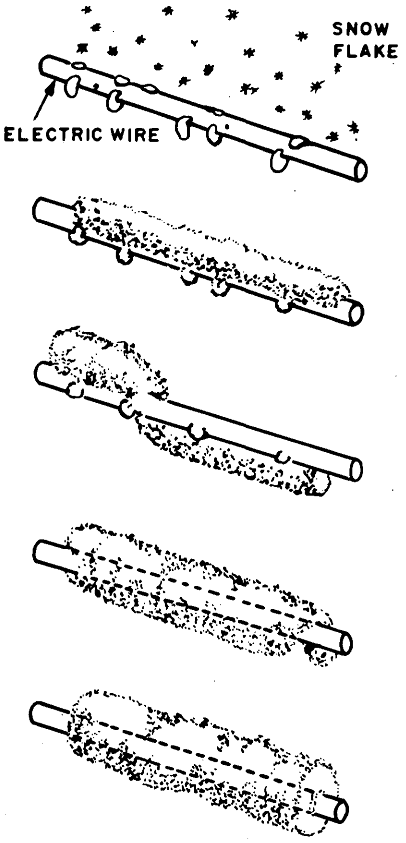

Figure 16. Snow accretion on wire.

When the air temperature falls, the wet snow freezes to the wire and becomes very difficult to remove. Figure 17 illustrates the relation between the diameter of snow accretion and its weight per meter length of wire. Dotted curves a and b represent lines calculated by assuming that snow accretions have a density of $\rho = 0.2$ and $\rho = 0.04$ respectively. Almost all observed data are dispersed between a and b. From this figure, one can assume that the weight of snow is about 1 kg/m for an accretion 10 cm in diameter and about 5 kg/m for a 20-cm accretion. Consequently, the electric wire will be elongated or cut by the heavy weight of snow accretion. Figure 18 shows the relationship between diameter of snow accretion and the accumulation of fallen snow. If the accumulation of snow on the ground surface is 2 g/cm^2, snow accretion on a wire will reach about 10 cm in diameter.

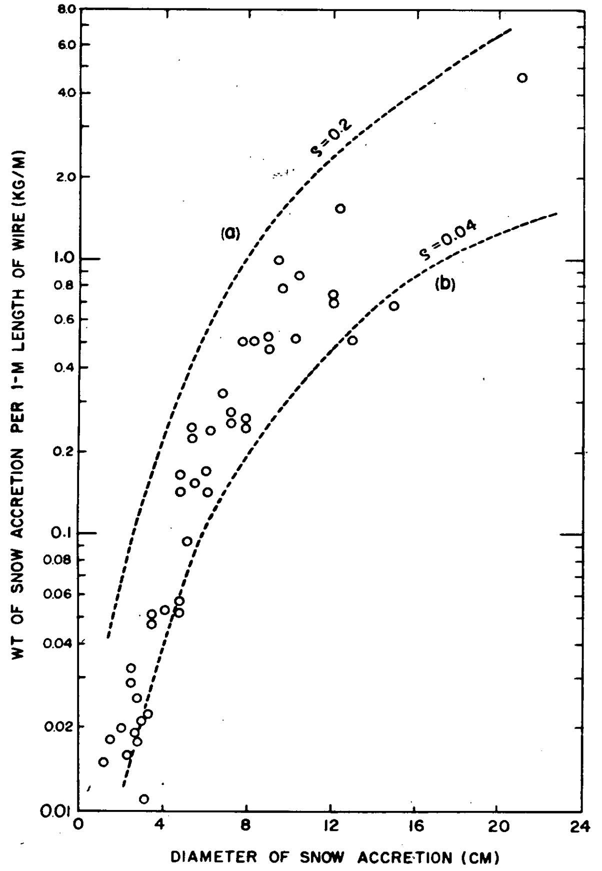

Figure 17. Relation between diameter of snow accretion and weight of snow. (Shoda, 1953)

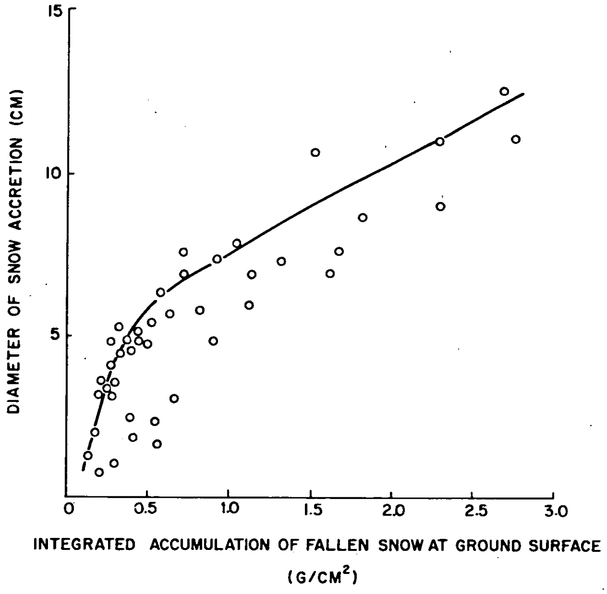

Figure 18. Relation between diameter of snow accretion and integrated snow accumulation. (Shoda, 1953)

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ICING AND SNOW ACCRETION ON ELECTRIC WIRES
by Daisuke Kuroiwa

Research Report 123, Jan 1965, 10p - illus.
DA Task 8X99-27-001-03
Unclassified Report

Experimental data on icing and snow accretion on electric wires and antennas is presented. The accumulation of supercooled droplets on a single wire stretched in an air flow has been calculated as icing in the form of soft rime, hard rime, and glaze, per unit time and unit length of wire. The difference between calculated values and observed values in Japan is discussed in terms of ice deposit, wire tension, and wind velocity and pressure. Iced wire will be cut more often by dynamic wind pressure than by the deposited ice load. The differences between icing and accretion of snow are discussed, the wire failures being attributed to the heavy weight of snow accretion. This phenomenon will be less frequent in polar regions than in temperate regions because the main cause of snow accretion— existence of a liquid-water film on the surface of snow flakes—is less prevalent. A simple experiment for anti-icing an electric wire by means of electrical heating is briefly described.

UNCLASSIFIED

1. Power lines--Meteorological effects
2. Ice formation--Meteorological effects
3. Antennas--Icing effects

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