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Snow accretion on overhead wires

Yukichi Sakamoto

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Snow accretion on overhead wires **cretion on overhead
By Yukichi Sakamo toj**

Central Research Institute for Electric Power Industry, 2-11-1, Iwatokita, Komae-shi, Tokyo 201-8511, Japan

Although snow accretion on overhead wires is a serious problem, recognized physical Although snow accretion on overhead wires is a serious problem, recognized physical
models have not yet been established. In this paper, attempts directed at under-
standing the mechanism of snow accretion on wires are rev Although snow accretion on overhead wires is a serious problem, recognized physical
models have not yet been established. In this paper, attempts directed at under-
standing the mechanism of snow accretion on wires are rev models have not yet been established. In this paper, attempts directed at under-
standing the mechanism of snow accretion on wires are reviewed. Fundamentals of
the meteorological conditions under which snow accretion are standing the mechanism of snow accretion on wires are reviewed. Fundamentals of
the meteorological conditions under which snow accretes on wires, inferred mecha-
nisms, mechanics and heat balance of snow accretion are brie the meteorological conditions under which snow accretes on wires, inferred mechanisms, mechanics and heat balance of snow accretion are briefly reviewed. A short historical review of research works throughout the world is nisms, mechanics and heat balance of snow accretion are briefly reviewed. A short
historical review of research works throughout the world is given. Wind-tunnel tests
aiming at examining the dependence of various parameter historical review of research works throughout the world is given. Wind-tunnel tests
aiming at examining the dependence of various parameters on the characteristics
of accreted snow on wires are introduced and defects of s aiming at examining the dependence of various parameters on the characteristics
of accreted snow on wires are introduced and defects of such tests are discussed.
Finally, attempts to establish snow-load design on power lin of accreted snow on wires are introduced and defects of such tests are discussed.
Finally, attempts to establish snow-load design on power lines, with some results of observations under natural conditions, are briefly disc Finally, attempts to establish snow-load design on power lines, with some results of observations under natural conditions, are briefly discussed. It should be emphasized that the present paper is characteristic of an inte that the present paper is characteristic of an interim report and summary about snow accretion on overhead wires, with the purpose of avoiding repetition of the that the present paper is characteristic of an interim report and summas
snow accretion on overhead wires, with the purpose of avoiding repetiti
same kind of research efforts and therefore accelerating further progress.

Exerch efforts and therefore accelerating further prog
Keywords: snow accretion; wet snow; loading design;
overhead wire: empirical modelling Keywords: snow accretion; wet snow; loading design;
overhead wire; empirical modelling

1. Introduction

Snow accretion on overhead lines is a type of icing classified as precipitation icing (see Show accretion on overhead lines is a type of icing classified as precipitation icing (see
IEC 1991). For other types of icing, such as glaze due to supercooled rain droplets
and rime ice due to supercooled cloud or for dr Snow accretion on overhead lines is a type of icing classified as precipitation icing (see
IEC 1991). For other types of icing, such as glaze due to supercooled rain droplets
and rime ice due to supercooled cloud or fog dr IEC 1991). For other types of icing, such as glaze due to supercooled rain droplets
and rime ice due to supercooled cloud or fog droplets, good physical models have
been developed. However, in the case of snow accretion, n and rime ice due to supercooled cloud or fog droplets, good physical models have
been developed. However, in the case of snow accretion, no satisfactory physical
model has yet been developed. There are several reasons why been developed. However, in the case of snow accretion, no satisfactory physical model has yet been developed. There are several reasons why this is so. Firstly, there are several physical mechanisms involved in the process of snow accretion. Secondly, there are difficulties encountered in simulating s there are difficulties encountered in simulating snow accretion under natural condithere are difficulties encountered in simulating snow accretion under natural conditions within the laboratory. Thirdly, snow accretion occurs under a wide variety and combination of conditions which make observations diff tions within the laboratory. Thirdly, snow accretion occurs under a wide variety and
combination of conditions which make observations difficult to assess, especially if
some combinations occur only rarely. Finally, it is combination of conditions which make observations difficult to assess, especially if
some combinations occur only rarely. Finally, it is often difficult to observe natural
snow accretion on wires after a snow event, since some combinations occur only rarely. Finally, it is often difficult to observe natural
snow accretion on wires after a snow event, since they might shed in a relatively short
time or change their characteristics rapidly in show accretion on wires after a snow event, since they might shed in a relatively short
time or change their characteristics rapidly in contrast to other types of accretion.
Japan consists of a group of islands extending a

time or change their characteristics rapidly in contrast to other types of accretion.
Japan consists of a group of islands extending along the sub-tropical zone to a lat-
itude of 45.5°, located at the boundary of the Paci Japan consists of a group of islands extending along the sub-tropical zone to a lat-
itude of 45.5°, located at the boundary of the Pacific Ocean and the Asian continent.
Thus, in every winter, snowfalls are experienced un itude of 45.5°, located at the boundary of the Pacific Ocean and the Asian continent.
Thus, in every winter, snowfalls are experienced under various synoptic meteorolog-
ical situations and, in particular, power lines suff Thus, in every winter, snowfalls are experienced under various synoptic meteorological situations and, in particular, power lines suffer many types of fault due to snow at very early stages of commissioning. Such faults ar

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(1) Breakage of wires and collapse of support structures due to snow overload on wires.
	- (2) Flashover between phases or between shield wire and phase conductor due to unequal sag increase between spans and phases of line, or wire movement due to simultaneous shedding of accreted snow.
	- (3) Interphase flashover, or wear of fittings and members including bolts, caused
by galloping motion of the wire due to aerodynamic instability when modified by galloping motion of the wire due to aerodynamic instability when modified
by galloping motion of the wire due to aerodynamic instability when modified
by snow accretion. Interphase flashover,
by galloping motion
by snow accretion. by galloping motion of the wire due to aerodynamic instability when modified
by snow accretion.
In addition, there are many problems experienced by overhead lines due to aval-

In addition, there are many problems experienced by overhead lines due to avalanche and snow cover settlement, but these are beyond the scope of the present paper and will not be discussed further. In addition, there are many probanche and snow cover settlement, but
and will not be discussed further.
Many of the above problems have che and snow cover settlement, but these are beyond the scope of the present paper
d will not be discussed further.
Many of the above problems have been studied by many researchers and engineers
Japan and there now exists

in Japan and there also problems have been studied by many researchers and engineers
in Japan and there now exists a considerable literature, but unfortunately most of
this is written in Japanese (see discussion given in t Many of the above problems have been studied by many researchers and engineers
in Japan and there now exists a considerable literature, but unfortunately most of
this is written in Japanese (see discussion given in the pap in Japan and there now exists
this is written in Japanese (see cof Electrical Engineers 1965).
Over some 40 years as a pow is is written in Japanese (see discussion given in the paper by the Japanese Institute
Electrical Engineers 1965).
Over some 40 years as a power line engineer I have collected and assessed a large
mber of papers on icing f

of Electrical Engineers 1965).
Over some 40 years as a power line engineer I have collected and assessed a large
number of papers on icing from my own country and other major cold regions. Prior
to 1982 only a few papers e Over some 40 years as a power line engineer I have collected and assessed a large
number of papers on icing from my own country and other major cold regions. Prior
to 1982 only a few papers existed on snow accretion. At th number of papers on icing from my own country and other major cold regions. Prior
to 1982 only a few papers existed on snow accretion. At this time, regular meetings
of the IWAIS (International Workshop on Atmospheric Icin to 1982 only a few papers existed on snow accretion. At this time, regular meetings
of the IWAIS (International Workshop on Atmospheric Icing of Structures) began
and many papers on snow accretion became available, especia of the IWAIS (International Workshop on Atmosphe
and many papers on snow accretion became available,
Iceland and the US (Alaska) and, of course, Japan.
During the preparation of this paper, the author had d many papers on snow accretion became available, especially from France, Spain,
pland and the US (Alaska) and, of course, Japan.
During the preparation of this paper, the author had another chance to assess these
pers and

Iceland and the US (Alaska) and, of course, Japan.
During the preparation of this paper, the author had another chance to assess these
papers and again experience the worries concerning the present-day understanding During the preparation of this paper, the author had another chance to assess these
papers and again experience the worries concerning the present-day understanding
of the physics of wet-snow accretion on overhead wires. papers and again experience the worries concerning the present-day understanding
of the physics of wet-snow accretion on overhead wires. The author presents in $\S 2$
material which highlights many of the difficulties enco of the physics of wet-snow accretion on overhead wires. The author presents in $\S 2$ material which highlights many of the difficulties encountered in the study of snow accretion and how some of them may be overcome, espe material
accretion
of view.

2. Fundamentals of snow accretion

(*a*) *Meteorological conditions under which snow accretion occurs*

(a) Meteorological conditions under which snow accretion occurs
In general, it has been considered that snow accretion on overhead lines occurs when
wet snowflakes' adhere to wires and this occurs at surface temperatures α is the snow of a show and the show accretion of states occurs when

"wet snowflakes' adhere to wires, and this occurs at surface temperatures just above

"Freezing" However in practice the phenomenon of snow accretio In general, it has been considered that snow accretion on overhead lines occurs when

"wet snowflakes' adhere to wires, and this occurs at surface temperatures just above

freezing. However, in practice, the phenomenon of wet snowflakes' adhere to wires, and this occurs at surface temperatures just above
freezing. However, in practice, the phenomenon of snow accretion is experienced
under a relatively wide range of combinations of meteorolo freezing. However, in practice, the phenomenon of snow accretion is experienced

under a relatively wide range of combinations of meteorological parameters.
Figure 1 shows an example of the time history of meteorological parameters during
snow accretion under positive temperature. These data were extra Figure 1 shows an example of the time history of meteorological parameters during
snow accretion under positive temperature. These data were extracted from records
of a nearby observatory when severe damage to power lines snow accretion under positive temperature. These data were extracted from records
of a nearby observatory when severe damage to power lines (including tower col-
lapses) was experienced. In this case, precipitation starte of a nearby observatory when severe damage to power lines (including tower collapses) was experienced. In this case, precipitation started at 17:00 on 22 March 1986, in the form of rain when the surface air temperature wa lapses) was experienced. In this case, precipitation started at 17:00 on 22 March 1986, in the form of rain when the surface air temperature was high $(+5 \degree C)$. At about 21:00 on the same day the temperature fell to *ca*. 1986, in the form of rain when the surface air temperature was high $(+5\degree C)$. At about 21:00 on the same day the temperature fell to $ca. +2\degree C$ and the precipitation changed to snow via sleet, with the temperature almost c tion changed to snow via sleet, with the temperature almost constant near $+0.5\,^{\circ}\mathrm{C}$ about 21:00 on the same day the temperature fell to $ca. +2$ °C and the precipitation changed to snow via sleet, with the temperature almost constant near $+0.5$ °C until precipitation ceased at about 21:00 the next day. At tion changed to snow via sleet, with the temperature almost constant near +0.5 °C
until precipitation ceased at about 21:00 the next day. At the latter temperature the
precipitation intensity was large, equivalent to more until precipitation ceased at about 21:00 the next day. At the latter temperature the precipitation intensity was large, equivalent to more than 5 mm h^{-1} of water, which is extremely high for the winter season. In add precipitation intensity was large, equivalent to more than 5 mm h^{-1} of water, which
is extremely high for the winter season. In addition, wind speeds of $ca.5-10 \text{ m s}^{-1}$
(ten minutes averaged) were observed during th *Phil. Trans. R. Soc. Lond.* A (2000)

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Figure 1. Meteorological data for the meteorological observation station.

Figure 1. Meteorological data for the meteorological observation station.
exact mass of snow accreted on wires was not measured, there was a sufficiently
heavy snow overload to promote the collapse of several towers exact mass of snow accreted on wires was not measured, there heavy snow overload to promote the collapse of several towers.
On the other hand, figure 2 shows the time history of meteore act mass of snow accreted on wires was not measured, there was a sufficiently
avy snow overload to promote the collapse of several towers.
On the other hand, figure 2 shows the time history of meteorological parameters
rin

heavy snow overload to promote the collapse of several towers.

On the other hand, figure 2 shows the time history of meteorological parameters

during the observation of snow accretion on an Ishiuchi test line (Niigata Pr On the other hand, figure 2 shows the time history of meteorological parameters
during the observation of snow accretion on an Ishiuchi test line (Niigata Prefec-
ture). The test line was constructed by the Central Researc during the observation of snow accretion on an Ishiuchi test line (Niigata Prefecture). The test line was constructed by the Central Research Institute of Electric Power Industry (CRIEPI), observed visually and monitored b ture). The test line was constructed by the Central Research Institute of Electric Power Industry (CRIEPI), observed visually and monitored by various instruments, including video camera. Figure 3 shows the time history of Power Industry (CRIEPI), observed visually and monitored by various instruments, including video camera. Figure 3 shows the time history of the measured mass of snow accreted on wires. During this accretion period, the win including video camera. Figure 3 shows the time history of the measured mass of snow accreted on wires. During this accretion period, the wind was calm and the speed could not be measured with an anemometer. Precipitation (snow) started at about 20:00 on 11 January 1986 and continued until 11:00 the speed could not be measured with an anemometer. Precipitation (snow) started at about 20:00 on 11 January 1986 and continued until 11:00 the next day. During the precipitation, the air temperature remained relatively cons about 20:00 on 11 January 1986 and continued until 11:00 the next day. During
the precipitation, the air temperature remained relatively constant, $ca. -4$ °C, and
a snow mass of $ca. 4 \text{ kg m}^{-1}$ accreted on wires due to the the precipitation, the air temperature as snow mass of ca. 4 kg m⁻¹ acc.
equivalent to 30 mm of water.
These limited experiences of the snow mass of ca . 4 kg m⁻¹ accreted on wires due to the accumulative precipitation
uivalent to 30 mm of water.
These limited experiences of the meteorological conditions under which snow accre-
on occurs can be summariz

equivalent to 30 mm of water.
These limited experiences of the meteorological conditions under which snow accretion occurs can be summarized as follows.

- (a) Snow accretion on overhead wires may occur at air temperatures as low as -7° C.
- (b) Snow accretion at sub-freezing temperatures is limited to extremely low wind Snow accretion at sub-speeds $(V \leq 2 \text{ m s}^{-1})$.). speeds $(V \leq 2 \text{ m s}^{-1})$.
(c) At temperatures above freezing, snow may accrete under any wind speed.
-
- (c) At temperatures above freezing, snow may accrete under any wind speed.

(d) Characteristics and growing processes of snow accretion are significantly dif-

ferent above and below a certain boundary temperature. The bou For competating above freezing, show may accrete and any wind speed.
Characteristics and growing processes of snow accretion are significantly dif-
ferent above and below a certain boundary temperature. The boundary tem-
p (d) Characteristics and growing processes of snow accretion are significantly different above and below a certain boundary temperature. The boundary temperature differs slightly depending upon the altitude of location abov ferent above and below a certain boundary temperature. The bound perature differs slightly depending upon the altitude of location absea level and the synoptic meteorological pattern causing snowfall.

Figure 2. Air temperature and accumulated precipitation rate during snow accretion.

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Figure 4. Growing process of a snow sleeve for dry-type accretion.

Because snow accretion giving rise to heavy load on power lines occurs at tem-Because snow accretion giving rise to heavy load on power lines occurs at temperatures above freezing with superposed relatively high precipitation intensity (wet snow) this paper concentrates on the process of wet-snow ac Because snow accretion giving rise to heavy load on power lines occurs at tem-
peratures above freezing with superposed relatively high precipitation intensity (wet
snow), this paper concentrates on the process of wet-snow peratures above freezing with superposed relatively high precipitation intensity (wet
snow), this paper concentrates on the process of wet-snow accretion. However, in
the following subsection, snow accretion at sub-freezin snow), this paper concentrates on the process of wet-snow accretion. However, in the following subsection, snow accretion at sub-freezing temperatures will be briefly described for completeness.

(*b*) *Snow accretion on overhead wires at sub-freezing temperatures*

In Ishiuchi, located in Niigata Prefecture (the Japan Sea side of the main island), In Ishiuchi, located in Niigata Prefecture (the Japan Sea side of the main island),
where the test lines were installed, many cases of snow accretion on wires were
observed for almost the same conditions as shown in figur In Ishiuchi, located in Niigata Prefecture (the Japan Sea side of the main island), where the test lines were installed, many cases of snow accretion on wires were observed for almost the same conditions as shown in figure % observed for almost the same conditions as shown in figure 2 (see Sakamoto *et al.* 1990); the growing process was also recorded and is conceptually depicted in figure 4. As shown in figure 4a, snow initially accumulate

1990); the growing process was also recorded and is conceptually depicted in figure 4.
As shown in figure 4*a*, snow initially accumulates as a pile on wires. In this stage, snow piled on the wire will be blown off if the As shown in figure 4*a*, snow initially accumulates as a pile on wires. In this stage, snow piled on the wire will be blown off if the wind speed is over 2 m s^{-1} . If snowfall continues under calm conditions, the heig continues under calm conditions, the height of the snow piled on the wire increases gradually and the top of the piled snow is inclined toward the wind and the incoming snowflake trajectories. The snow piled on the wire no gradually and the top of the piled snow is inclined toward the wind and the incomgradually and the top of the piled snow is inclined toward the wind and the incom-
ing snowflake trajectories. The snow piled on the wire now suddenly begins to creep
into the wind (as shown in figure 4b). This is the seco ing snowflake trajectories. The snow piled on the wire now suddenly begins to creep
into the wind (as shown in figure $4b$). This is the second stage of the growing pro-
cess. The speed of creep is in general relatively h into the wind (as shown in figure 4b). This is the second stage of the growing process. The speed of creep is in general relatively high, and when viewed from the downstream side of the wire the piled snow disappears from reappears. The speed of creep is in general relatively high, and when viewed from the downstream side of the wire the piled snow disappears from the top of the wire and reappears at the bottom within 5 min. If snowfall con downstream side of the wire the piled snow disappears from the top of the wire and
reappears at the bottom within 5 min. If snowfall continues, the piling and creeping
of snow repeats, and finally a cylindrical snow sleev reappears at the bottom within 5 min. If snowfall continues, the piling and creeping
of snow repeats, and finally a cylindrical snow sleeve is formed via the processes
depicted in figure 4c, d. It should be noted that the of snow repeats, and finally a cylindrical snow sleeve is formed via the processes depicted in figure $4c, d$. It should be noted that the density of snow accreted during these processes at sub-freezing temperature is in g depicted in figure 4*c*, *d*. It should be noted that the density of snow acing these processes at sub-freezing temperature is in general very low exceeds 0.1 g cm⁻³; moreover, the adhesive force will be also very low.
 g these processes at sub-freezing temperature is in general very low and never
ceeds 0.1 g cm^{-3} ; moreover, the adhesive force will be also very low.
The cases depicted in figure 4 are an example of ideal growth. In ma

The cases depicted in figure 4 are an example of ideal growth. In many cases, snow piled on wires drops spontaneously during the second and third stages of growth. This is especially true for wires of small size and low torsional rigidity, or under piled on wires drops spontaneously during the second and third stages of growth.
This is especially true for wires of small size and low torsional rigidity, or under
relatively high wind speed (for example, 1.5 m s^{-1} This is especially true for wires of small size and low torsional rigidity, or under relatively high wind speed (for example, 1.5 m s^{-1}) when the wire begins to twist and piled snow tends to drop off, not allowing th relatively high wind speed (for example, 1.5 m s^{-1}) when the wire begins to twist
and piled snow tends to drop off, not allowing the creep stage to start. Consequently,
growth of this kind of snow accretion under sub and piled snow tends to drop off, not allowing the creep stage to start. Consequently,
growth of this kind of snow accretion under sub-freezing temperatures (dry-type snow
accretion) will be limited to low- or medium-volta growth of this kind of snow accretion under sub-freezing temperatures (dry-type snow accretion) will be limited to low- or medium-voltage lines having low height above ground and shielded against wind action. In addition, accretion) will be limited to low- or medium-voltage lines having low height above
ground and shielded against wind action. In addition, it is inferred that this type will
scarcely give rise to high overload governing mech ground and shielded against wind action. In addition, it is inferred that this type will

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snow sleeve is formed around the entire span of the wire, it tends to drop simultasnow sleeve is formed around the entire span of the wire, it tends to drop simulta-
neously, and may cause jumping of the wire due to transformation of the potential
energy stored in the wire to kinetic energy through incr snow sleeve is formed around the entire span of the wire, it tends to drop simultaneously, and may cause jumping of the wire due to transformation of the potential energy stored in the wire to kinetic energy through increa energy stored in the wire to kinetic energy through increased wire tension. Inferred mechanisms leading to snow accretion will be discussed in the following section.

(*c*) *Inferred mechanisms of snow accretion on overhead wires*

For snow accretion to form a cylindrical sleeve (causing heavy overload to power For snow accretion to form a cylindrical sleeve (causing heavy overload to power
lines without shedding) there must be an adhesive force between the surface of the
wire and the snow accumulation and between snowflakes the For snow accretion to form a cylindrical sleeve (causing heavy overload to power
lines without shedding) there must be an adhesive force between the surface of the
wire and the snow accumulation and between snowflakes them lines without shedding) there must be an adhesive force between the surface of the
wire and the snow accumulation and between snowflakes themselves. Indeed, if these
adhesive forces do not exist, then all snowflakes piled wire and the snow accumulation and between snowflakes themselves. Indeed, if these adhesive forces do not exist, then all snowflakes piled on the wire will be blown off by wind and not observed to adhere. In the cases in w by wind and not observed to adhere. In the cases in which heavy load on wires has by wind and not observed to adhere. In the cases in which heavy load on wires has
been experienced, cylindrical snow sleeves have been observed without exception and
the mechanism for such growth depends on adhesive forces been experienced, cylindrical snow sleeves have been observed without exception and
the mechanism for such growth depends on adhesive forces. Some of the origins of
adhesive forces between the surface of wires and snowflak the mechanism for such gro
adhesive forces between the
themselves, are as follows. adhesive forces between the surface of wires and snowflakes, and between snowflakes
themselves, are as follows.
(1) Freezing (including pressure melting, re-freezing).

-
- (1) Freezing (including pressure melting, re-freezing).

(2) Bonding through freezing of supercooled water droplets existing on the surface

of snowflakes. Bonding through
of snowflakes. of snowflakes.
(3) Sintering.
-
- (4) Condensation and freezing of vapour in the air.
- (5) Mechanical intertwining of snowflakes.
- (6) Capillary action due to liquid water included.
- (7) Coherent force between ice particles formed through metamorphosis of snow flakes.

In general, the occurrence of freezing is limited to below 0° C, and bonding action of In general, the occurrence of freezing is limited to below 0° C, and bonding action of supercooled droplets is also expected below 0° C (although, in temperatures slightly above 0° C freezing can occur through In general, the occurrence of freezing is limited to below $0^{\circ}C$, and bonding action of supercooled droplets is also expected below $0^{\circ}C$ (although, in temperatures slightly above $0^{\circ}C$, freezing can occur throug sublimation, but this e¬ect is expected to be small). ove 0° C, freezing can occur through dissipation of heat with evaporation and
blimation, but this effect is expected to be small).
Therefore, in cases where the air temperature is relatively low, adhesive mecha-
sms (

sublimation, but this effect is expected to be small).
Therefore, in cases where the air temperature is relatively low, adhesive mechanisms (2) , (3) , (4) and (5) are expected to dominate. Of course, the occurrence Therefore, in cases where the air temperature is relatively low, adhesive mechanisms (2) , (3) , (4) and (5) are expected to dominate. Of course, the occurrence of freezing can be expected, but in sub-freezing tempe nisms (2) , (3) , (4) and (5) are expected to dominate. Of course, the occurrence of freezing can be expected, but in sub-freezing temperatures it has been confirmed that the liquid-water content of snowflakes is ve freezing can be expected, but in sub-freezing temperatures it has been confirmed
that the liquid-water content of snowflakes is very low. On the other hand, in cases
where the temperature is higher, mechanisms (6) and (7) at the liquid-water content of snowflakes is very low. On the other hand, in cases
nere the temperature is higher, mechanisms (6) and (7) are expected to dominate.
Thus, dominant adhesive mechanisms are influenced by

where the temperature is higher, mechanisms (6) and (7) are expected to dominate.
Thus, dominant adhesive mechanisms are influenced by the liquid-water content
of snowflakes, air temperature, humidity and speed of air Thus, dominant adhesive mechanisms are influenced by the liquid-water content
of snowflakes, air temperature, humidity and speed of air carrying snowflakes. The
action of wind is threefold: it compacts the accreted snow; i of snowflakes, air temperature, humidity and speed of air carrying snowflakes. The action of wind is threefold: it compacts the accreted snow; it increases the impact speed of snowflakes on wires or snow sleeves; and it ac action of wind is tl
speed of snowflakes
of accreted snow.
Generally speaki eed of snowflakes on wires or snow sleeves; and it accelerates the metamorphosis
accreted snow.
Generally speaking, the liquid-water content of the snow is higher when the air
more speaking is higher However, it is not tru

of accreted snow.
Generally speaking, the liquid-water content of the snow is higher when the air
temperature is higher. However, it is not true that there is no liquid water included
in snowflakes in sub-freezing temperat Generally speaking, the liquid-water content of the snow is higher when the air temperature is higher. However, it is not true that there is no liquid water included in snowflakes in sub-freezing temperatures. This is bec in snowflakes in sub-freezing temperatures. This is because water is a substance that can be kept at liquid state at temperatures as low as $-35 \degree C$ without ice nuclei

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and also it has a relatively high specific heat. The ice crystal itself is enriched in
ice nuclei, and whether the liquid water contained in a snowflake is frozen or not ice nuclei, and whether the liquid water contained in a snowflake is frozen or not
is governed by the heat balance for the flakes. For example, when an atmospheric and also it has a relatively high specific heat. The ice crystal itself is enriched in
ice nuclei, and whether the liquid water contained in a snowflake is frozen or not
is governed by the heat balance for the flakes. For ice nuclei, and whether the liquid water contained in a snowflake is frozen or not
is governed by the heat balance for the flakes. For example, when an atmospheric
layer with a temperature above freezing exists over a near

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is governed by the heat balance for the flakes. For example, when an atmospheric
layer with a temperature above freezing exists over a near-ground sub-freezing layer,
and when some portion of the ice inside the flakes is m layer with a temperature above freezing exists over a near-ground sub-freezing layer,
and when some portion of the ice inside the flakes is melted, liquid water will exist,
even when the surface temperature is sub-freezing and when some portion of the ice inside the flakes is melted, liquid water will exist,
even when the surface temperature is sub-freezing, until latent heat is dissipated by
heat exchange. Therefore, strictly speaking, the even when the surface temperature is sub-freezing, until latent heat is dis
heat exchange. Therefore, strictly speaking, the boundary between wet snow
snow cannot be defined simply on the basis of the surface temperature.

at exchange. Therefore, strictly speaking, the boundary between wet snow and dry
ow cannot be defined simply on the basis of the surface temperature.
As mentioned previously, the characteristics of accreted snow and growth show cannot be defined simply on the basis of the surface temperature.
As mentioned previously, the characteristics of accreted snow and growth processes
are strongly dependent on adhesive mechanisms. However, the author c As mentioned previously, the characteristics of accreted snow and growth processes
are strongly dependent on adhesive mechanisms. However, the author considers that
it is acceptable to distinguish wet snow from dry snow ba are strongly dependent on adhesive mechanisms. However, the author considers that it is acceptable to distinguish wet snow from dry snow based on surface air temperature (that is, above or below freezing) from the standpoi it is acceptable to distinguish wet snow from dry snow based on surface air temperature (that is, above or below freezing) from the standpoint of the phenomenon that occurs on power lines, rather than attempting to employ arguments. curs on power lines, rather than attempting to employ physical or meteorological
guments.
Indeed, the author suspects that for dry snow the dominant adhesive forces are
essure melting (re-freezing) and sintering (Sakamoto

pressure melting (re-freezing) and sintering (Sakamoto *et al.* 1990), and for wet
snow capillary forces due to liquid water and coherent forces between ice particles Indeed, the author suspects that for dry snow the dominant adhesive forces are pressure melting (re-freezing) and sintering (Sakamoto *et al.* 1990), and for wet snow, capillary forces due to liquid water and coherent for pressure melting (re-freezing) and sintering (Sakamoto *et al.* 1990), and for wet
snow, capillary forces due to liquid water and coherent forces between ice particles
formed through the metamorphosis of snowflakes domina snow, capillary forces due to liquid water and coherent forces between ice particles formed through the metamorphosis of snowflakes dominate. It should be noted that Colbeck $\&$ Ackley (1982) presented similar mechanisms formed through t
Colbeck & Ackle
snow accretion.
In addition it. Colbeck & Ackley (1982) presented similar mechanisms for the formatting of wet-
snow accretion.
In addition, it should be noted that if the temperature falls below freezing after

snow accretion.
In addition, it should be noted that if the temperature falls below freezing after
wet snow has accreted on a wire, it will then freeze. When this happens, the adhesive
force is significant, due to the hydr In addition, it should be noted that if the temperature falls below freezing after
wet snow has accreted on a wire, it will then freeze. When this happens, the adhesive
force is significant, due to the hydrogen bond betwee wet snow has accreted on a wire, it will then freeze. When this happens, the adhesive
force is significant, due to the hydrogen bond between the wire surface and the ice
particles, and also bonding between ice particles wi force is significant, due to the hydrogen bond between the wire surface and the ice
particles, and also bonding between ice particles will be enhanced due to freezing. particles, and also bonding between ice particles will be enhanced due to freezing.
In such instances, a wet-snow sleeve is hardly shed, even under strong winds, and
may give rise to high combinations of snow and wind load In such instances, a wet-snow sleeve is hardly shed, even under strong winds, and may give rise to high combinations of snow and wind load, and may also cause galloping. When sleet falls are experienced, the solid-state ic may give rise to high combinations of snow and wind load, and may also cause galloping. When sleet falls are experienced, the solid-state ice contained in the sleet may be frozen on the wires through heat dissipation by ev galloping. When sleet falls are experienced, the solid-state ice contained in the sleet

(*d*) *Mechanics of snow accretion on overhead wires*

The shape of snow accreted on overhead wires is governed by many factors, includ-The shape of snow accreted on overhead wires is governed by many factors, includ-
ing: meteorological parameters such as temperature, humidity, wind speed and wind
direction relative to lines: and line parameters such as The shape of snow accreted on overhead wires is governed by many factors, includ-
ing: meteorological parameters such as temperature, humidity, wind speed and wind
direction relative to lines; and line parameters such as m ing: meteorological parameters such as temperature, humidity, wind speed and wind
direction relative to lines; and line parameters such as material, size, stranding, sup-
porting manner and span length. The shape of the ac direction relative to lines; and line parameters such as material, size, stranding, supporting manner and span length. The shape of the accreted snow, as well as its orientation on a wire, may enhance the formation of cyli porting manner and span length. The shape of the accrocientation on a wire, may enhance the formation of cylical to heavy overload, and it may also cause galloping.
Obviously the shape of the wire effects the growing proce orientation on a wire, may enhance the formation of cylindrical sleeve growth and lead to heavy overload, and it may also cause galloping.
Obviously, the shape of the wire effects the growing process. Although this problem

has no direct relation to overhead-line loading, it nevertheless should be investigated
has no direct relation to overhead-line loading, it nevertheless should be investigated
so as to yield a better understanding of snow Obviously, the shape of the wire effects the growing process. Althorney has no direct relation to overhead-line loading, it nevertheless shouls on as to yield a better understanding of snow accretion on wires. In Japan it In Japan, it was assumed that wet-snow accretion on wires.
In Japan, it was assumed that wet-snow accretion is a phenomenon which occurs
In Japan, it was assumed that wet-snow accretion is a phenomenon which occurs
In Japa

so as to yield a better understanding of snow accretion on wires.
In Japan, it was assumed that wet-snow accretion is a phenomenon which occurs
only under low wind speed. Shoda (1953) installed a test line in Shiozawa (Nii In Japan, it was assumed that wet-snow accretion is a phenomenon which occurs
only under low wind speed. Shoda (1953) installed a test line in Shiozawa (Niigata
Prefecture) and made observations under natural conditions ov only under low wind speed. Shoda (1953) installed a test line in Shiozawa (Niigata Prefecture) and made observations under natural conditions over long periods. He reports that the growing process on a solid wire (a cylind Prefecture) and made observations under natural correports that the growing process on a solid wire (a cylinused mainly for communication lines was as follows. used mainly for communication lines was as follows.
(1) First stage: piling of snow on wire.

-
- (2) Second stage: sliding of accreted snow on wire, without twisting of wire.

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- (3) Repetition of first and second stages.
- (4) Formation of cylindrical snow sleeve without twisting of wire.

(4) Formation of cylindrical snow sleeve without twisting of wire.
Growing processes in accord with his observations are illustrated schematically in
ure 5. These processes have been confirmed for a larger size (diameter Growing processes in accord with his observations are illustrated schematically in figure 5. These processes have been confirmed for a larger size (diameter of 2 cm) smooth cylinder using wind-tunnel facilities to sug Growing processes in accord with his observations are illustrated schematically in figure 5. These processes have been confirmed for a larger size (diameter of 2 cm) smooth cylinder using wind-tunnel facilities to sug figure 5. These processes have been confirmed for a larger size (diameter of 2 cm) smooth cylinder using wind-tunnel facilities to suggest a kind of countermeasure for reducing snow mass on wires. That is, when a tiny fin is placed around covered of cylindrical snow sleeves is prevented.
The development of cylindrical snow-sleeve growth on a stranded wire, as used for conductors, the snow piled on the wire cannot slip around the wire and the formation

power lines, is completely different from the above (see Admirat *et al.* 1986; Admirat The development of cylindrical snow-sleeve growth on a stranded wire, as used for
power lines, is completely different from the above (see Admirat *et al.* 1986; Admirat
& Sakamoto 1988). Here, the growth rate depends on power lines, is completely different from the above (see Admirat *et al.* 1986; Admirat & Sakamoto 1988). Here, the growth rate depends on the torsion of the wire. The growing processes for a cylindrical snow sleeve around & Sakamoto 1988). Here, the growing processes for a cy schematically in figure 6.
In the centre of the wire growing processes for a cylindrical snow sleeve around a stranded wire are shown
schematically in figure 6.
In the centre of the wire span, where the wire is horizontal, there is no slippage or

schematically in figure 6.
In the centre of the wire span, where the wire is horizontal, there is no slippage or
relative movement between the wire surface and accreted snow. Moreover, since the
torsional rigidity of the w In the centre of the wire span, where the wire is horizontal, there is no slippage or relative movement between the wire surface and accreted snow. Moreover, since the torsional rigidity of the wire, especially in centre p relative movement between the wire surface and accreted snow. Moreover, since the torsional rigidity of the wire, especially in centre portion of a long span, is relatively low, the wire is easily twisted around its axis d torsional rigidity of the wire, especially in centre portion of a long span, is relatively
low, the wire is easily twisted around its axis due to the twisting moment induced by
the eccentric weight of accreted snow. As dis low, the wire is easily twisted around its axis due to the twisting moment induced by
the eccentric weight of accreted snow. As discussed later, wet snow tends to accrete
on the windward side of the wire under medium- or h the eccentric weight of accreted snow. As discussed later, wet snow tends to accrete
on the windward side of the wire under medium- or high-wind conditions, and the
rotating of the wire is further increased by the effect o on the windward side of the wire under medium- or high-wind conditions, and the rotating of the wire is further increased by the effect of wind pressure. Also, the shape of the snow accreted on a wire differs as a functio rotating of the wire is further increased by the effect of wind pressure. Also, the shape
of the snow accreted on a wire differs as a function of locations along the wire span.
This snow accretion problem is studied in de This snow accretion problem is studied in detail in Poots & Skelton (1988, 1993)
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Figure 6. Wet-snow accretion on a stranded wire having low torsional rigidity.

Figure 6. Wet-snow accretion on a stranded wire having low torsional rigidity.
and Poots (1996). Here, time-dependent models are developed which incorporate the
effect of wind pressure and the torsional properties of the w and Poots (1996). Here, time-dependent models are developed where
effect of wind pressure and the torsional properties of the wire.
It has also been observed that, at least initially snow accreted d Poots (1996). Here, time-dependent models are developed which incorporate the
fect of wind pressure and the torsional properties of the wire.
It has also been observed that, at least initially, snow accreted slightly abo

effect of wind pressure and the torsional properties of the wire.
It has also been observed that, at least initially, snow accreted slightly above the
centre of the windward side of the wire, and then suddenly the wire tw It has also been observed that, at least initially, snow accreted slightly above the centre of the windward side of the wire, and then suddenly the wire twisted more than 10° on further accretion. Thus the mass of sn centre of the windward side of the wire, and then suddenly the wire twisted more
than 10° on further accretion. Thus the mass of snow accreted will be greater in
the centre portion of the span and lesser closer to ei than 10° on further accretion. Thus the mass of snow accreted will be greater in the centre portion of the span and lesser closer to either end of the span. These observations suggest that when the torsional rigidity the centre portion of the span and lesser closer to either end of the span. These
observations suggest that when the torsional rigidity of the wire is increased, the
mass of the accreted snow will decrease. Experiments on observations suggest that when the torsional rigidity of the wire is increased, the mass of the accreted snow will decrease. Experiments on attaching counterweights to a span to increase the torsional rigidity of the wire mass of the accreted snow will decrease. Experiments on attaching counterweights
to a span to increase the torsional rigidity of the wire have been undertaken in France
and Japan and proved to be effective in reducing load to a span to increase the torsional rigidity of the wire have been undertaken in France
and Japan and proved to be effective in reducing load in some cases; to date, the
effectiveness of such countermeasures have not been and Japan and proved to be effective in reducing load in some cases; to date, the effectiveness of such countermeasures have not been fully evaluated in Japan. Wetsnow accretion on a torsionally rigid wire is shown schemat effectiveness of such countermeasures have not been fully evaluated in Japan. Wetsnow accretion on a torsionally rigid wire is shown schematically in figure 7. It can be seen that an increase of the area projected to the w snow accretion on a torsionally rigid wire is shown schematically in figure 7. It can be
seen that an increase of the area projected to the wind in which snow accreted further
will be smaller, and the accretion efficiency seen that an increase of the area projected to the wind in which snow accreted further will be smaller, and the accretion efficiency will be smaller, due to the trajectories of snowflakes around the wire (see Wakahama 1979

(*e*) *Heat balance during snow accretion*

(e) Heat balance during snow accretion
The study of the heat balance for the accreted snow provides information on
alting and the prevention of accretion by load current of power lines. This was The study of the heat balance for the accreted snow provides information on
melting and the prevention of accretion by load current of power lines. This was
first analysed by Grenier et al. (1986) and Admirat et al. (1988 The study of the heat balance for the accreted snow provides information on
melting and the prevention of accretion by load current of power lines. This was
first analysed by Grenier *et al.* (1986) and Admirat *et al.* (1 melting and the prevention of accretion by load current of power lines. This was
first analysed by Grenier *et al.* (1986) and Admirat *et al.* (1988*a*) (see the summary
of Poots 1996). The relevant heat fluxes incorpora first analysed by Grenier et al . (1986) and of Poots 1996). The relevant heat fluxes cylindrical-sleeve growth are as follows: s follows:
 $Q_{\rm A} = Jh(T_{\rm A} - T_{\rm S})\pi D,$ (2.1)

$$
Q_{\rm A} = Jh(T_{\rm A} - T_{\rm S})\pi D,\tag{2.1}
$$

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Figure 7. Wet-snow accretion on a torsionally rigid stranded wire.

Figure 7. Wet-snow accretion on a torsionally rigid stranded wire.
where Q_A is the heat supplied through convection $(W \text{ cm}^{-1})$, J is the mechan-
ical equivalent of heat $(J = 4.186 \text{ J} \text{ cal}^{-1})$. h is the coefficient o where Q_A is the heat supplied through convection $(W cm^{-1})$, J is the mechanical equivalent of heat $(J = 4.186 J \text{ cal}^{-1})$, h is the coefficient of heat transfer (cal cm⁻² s⁻¹ °C). T_A is the air temperature (°C). T where Q_A is the heat supplied through convection $(W \text{ cm}^{-1})$, J is the mechanical equivalent of heat $(J = 4.186 \text{ J cal}^{-1})$, h is the coefficient of heat transfer (cal cm⁻² s⁻¹ °C), T_A is the air temperature (°C) ical equivalent of heat $(J = 4.186 \text{ J cal}^{-1})$, h is the coefficient of (cal cm⁻² s⁻¹ °C), T_A is the air temperature (°C), T_S is the temperature surface accreted (°C), and D is the diameter of accreted snow (cm).
The al cm⁻² s⁻¹ °C), T_A is the air temperature (°C), T_S is the temperature of snow
rface accreted (°C), and D is the diameter of accreted snow (cm).
The coefficient of heat trasnfer (h) is related to the Nusselt numbe

surface accreted ($^{\circ}$ C), and *D* is the diameter of accreted snow (cm).
The coefficient of heat trasnfer (*h*) is related to the Nusselt number *Nu*, and is expressed as follows: $h = (\lambda/D)Nu,$ (2.2)

$$
h = (\lambda/D)Nu,\t\t(2.2)
$$

 $h = (\lambda/D)Nu,$ (2.2)
where λ is the thermal conductivity of air. Furthermore, Nu is related to the Reynolds
number Be and Grenier *et al.* (1985) have proposed the following approximation: where λ is the thermal conductivity of air. Furthermore, Nu is related to the Reynolds
number Re , and Grenier *et al.* (1985) have proposed the following approximation: number Re , and Grenier *et al.* (1985) have proposed the following approximation:

$$
Nu = 0.2 Re^{0.61} \quad \text{(for } Re \leq 10^4\text{)}.
$$
 (2.3)

The Reynolds number is defined by

$$
Re = V \rho_A / \mu, \qquad (2.4)
$$

 $Re = V \rho_A / \mu,$ (2.4)
where V is the horizontal wind speed (cm s⁻¹), ρ_A is the density of air at temperature
 T_A (g cm⁻³) and μ is the kinematic viscosity of air at temperature T_A (g cm⁻¹ s⁻¹) where V is the horizontal wind speed (cm s^{-1}) , ρ_A is the density of air at temperature T_A (g cm⁻¹ s⁻²), and μ is the kinematic viscosity of air at temperature T_A (g cm⁻¹ s⁻²), winds s^{-1}). here *V* is the horizontal wind speed (cm s^{-1}) , ρ_A is the $(g \text{ cm}^{-3})$, and μ is the kinematic viscosity of air at to Substituting (2.2), (2.3) and (2.4) into (2.1) yields Substituting (2.2) , (2.3) and (2.4) into (2.1) yields

$$
Q_{\rm A} = 2.63 \lambda (\rho_{\rm A}/\mu)^{0.61} (VD)^{0.61} (T_{\rm A} - T_{\rm S}). \tag{2.5}
$$

 $Q_{\rm A} = 2.63 \lambda (\rho_{\rm A}/\mu)^{0.61} (VD)^{0.61} (T_{\rm A} - T_{\rm S}).$ (2.5)
In cases of wet snow, $T_{\rm A}$ is above freezing and hence ice and liquid water coexist;
follows that $T_{\rm A} = 0$ °C. Employing the values $\rho_{\rm S} = 1.293 \times 10$ In cases of wet snow, T_A is above freezing and hence ice and liquid water coexist;
it follows that $T_A = 0$ °C. Employing the values $\rho_S = 1.293 \times 10^{-3}$ (g cm⁻³) and
 $\mu = 1.73 \times 10^{-4}$ (g cm⁻¹ s⁻¹) yields the foll In cases of wet snow, T_A is above freezing and hence ice and lique it follows that $T_A = 0$ °C. Employing the values $\rho_S = 1.293 \times 10^{14}$ (g cm⁻¹ s⁻¹) yields the following approximation: S^{-1}) yields the following approxim
 $Q_A = 0.52(VD)^{0.61}T_A \times 10^3$.

$$
Q_A = 0.52(VD)^{0.61} T_A \times 10^3. \tag{2.6}
$$

 $Q_A = 0.52(VD)^{0.61} T_A \times 10^3.$ (2.6)
For the case when T_A is negative (that is, sub-freezing), it may be assumed that
 $= T_G$ and $Q_A = 0$ $T_A = T_S$ and $Q_A = 0$.
Since the wire carries electric current, ohmic heating of the wire is supplied to the For the case when T_A is negative (that is, sub-freezing), it may be assumed that T_S and $Q_A = 0$.
Since the wire carries electric current, ohmic heating of the wire is supplied to the ownersted by conduction. The Joule

 $T_A = T_S$ and $Q_A = 0$.
Since the wire carries electric current, ohmic heating of the wire is supplied to the
snow accreted by conduction. The Joule heat generated by current Q_J (W cm⁻¹)
may be calculated as follows: $)$ Since the wire carries electric
snow accreted by conduction.
may be calculated as follows:

$$
Q_{\rm J} = I^2 R_{\rm AC\,T_{\rm C}},\tag{2.7}
$$

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Snowaccretiononoverhead wires ²⁹⁵¹

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where R_{ACT_C} (Ω cm⁻¹) is resistance of wire for alternating current at temperature
 T_C and is given by where $R_{\text{AC}T_{\text{C}}}$ (Ω cm⁻⁷
 T_{C} and is given by

$$
R_{\text{ACT}_\text{C}} = K_1 K_2 R_{\text{DC20}} \times 10^{-5} \{ 1 + w_{20} (T_\text{C} - 20) \},\tag{2.8}
$$

 $R_{\text{AC }T_{\text{C}}} = K_1 K_2 R_{\text{DC}20} \times 10^{-5} \{1 + w_{20}(T_{\text{C}} - 20)\},$ (2.8)
where w_{20} is the thermal coefficient of resistance of the wire at 20 °C, $R_{\text{DC}20}$ is the
resistance of the wire for direct current at 20 °C ($\$ where w_{20} is the thermal coefficient of resistance of the wire at 20 °C, R_{DC20} is the resistance of the wire for direct current at 20 °C (Ω cm⁻¹), K_1 is the factor taking into account the skin effect of resistance of the wire for direct current at 20 °C (Ω cm⁻¹), K_1 is the factor taking into account the skin effect of the wire, and K_2 is the factor taking into account the eddy current loss of the wire, includi resistance of the wire for direct current at 20 °C (Ω cm⁻¹), K_1 is the factor taking
into account the skin effect of the wire, and K_2 is the factor taking into account the
eddy current loss of the wire, includi into account the skin effect of the wire, and K eddy current loss of the wire, including the f
calculated by the following approximations: calculated by the following approximations:

$$
K_1 = 1 + 1.56 \times 10^3 \{0.05 \sqrt{f} / R_{\text{DC20}}\}^{3.93} \tag{2.9}
$$

and

$$
K_2 = \begin{cases} 1 & \text{for small ACSR,} \\ 1.025 & \text{for larger ACSR,} \end{cases}
$$
 (2.10)

where ACSR refers to aluminium conductor steel reinforced wire.

For wet-snow accretion, vapour pressure at the surface may be assumed to be at the saturated value, since ice and water are co-existent. If a difference exists For wet-snow accretion, vapour pressure at the surface may be assumed to be
at the saturated value, since ice and water are co-existent. If a difference exists
between the saturated vapour pressure and the vapour pressure at the saturated value, since ice and water are co-existent. If a difference exists
between the saturated vapour pressure and the vapour pressure of the surrounding
air, then evaporation or condensation occurs. Heat loss (between the saturated vapour pressure and
air, then evaporation or condensation occur
(or condensation) is expressed as follows: expressed as follows:
 $Q_C = h(Pr/Sc)^{0.63}(L_V/C_p)\varepsilon(\Delta P_C/P)\pi D,$ (2.11)

$$
Q_{\rm C} = h(Pr/Sc)^{0.63} (L_{\rm V}/C_p) \varepsilon (\Delta P_{\rm C}/P) \pi D, \tag{2.11}
$$

 $Q_C = h(Pr/Sc)^{0.63}(L_V/C_p)\varepsilon(\Delta P_C/P)\pi D,$
where h is the coefficient of heat transfer by convection (cal cm⁻² s⁻
the Prandtl number (equal to $\mu \times C_c/\lambda \approx 0.718$ at 0° C). Sc is the Sq s^{-1} °C), Pr is where h is the coefficient of heat transfer by convection (cal cm⁻² s⁻¹ °C), Pr is
the Prandtl number (equal to $\mu \times C_p/\lambda \approx 0.718$ at 0 °C), Sc is the Schmidt num-
her (equal to $\mu/\rho_{\lambda} \times D_P \approx 0.608$ at 0 °C). Ly is where h is the coefficient of heat transfer by convection (cal cm⁻² s⁻¹°C), Pr is
the Prandtl number (equal to $\mu \times C_p/\lambda \approx 0.718$ at 0°C), Sc is the Schmidt num-
ber (equal to $\mu/\rho_A \times D_B \approx 0.608$ at 0°C), L_V is the the Prandtl number (equal to $\mu \times C_p/\lambda \approx 0.718$ at 0° C), *Sc* is the Schmidt num-
ber (equal to $\mu/\rho_A \times D_B \approx 0.608$ at 0° C), L_V is the vaporization heat of water
(equal to 2500 J g⁻¹), C_p is the specific h ber (equal to $\mu/\rho_A \times D_B \approx 0.608$ at 0° C), L_V is the vaporization heat of water
(equal to 2500 J g⁻¹), C_p is the specific heat of air at constant pressure (equal to
0.24 cal g⁻¹°C), P_C is the difference bet (equal to 2500 J g⁻¹), C_p is the specific heat of air at constant pressure (equal to 0.24 cal g⁻¹°C), P_C is the difference between vapour pressure of air at T_A and saturated vapour pressure of air at 0[°]C (Pa), 0.24 cal g⁻¹°C), P_C is the difference between vapour pressure of air at T_A and saturated vapour pressure of air at 0°C (Pa), P is the atmospheric pressure (Pa), D is the outer diameter of accreted snow (cm), and urated vapour pressure of air at 0° C
is the outer diameter of accreted snot
water vapour in air (equal to 0.22).
In the case when $P = 1000$ Pa the is the outer diameter of accreted snow (cm), and D_B is the diffusion coefficient of water vapour in air (equal to 0.22).

In the case when $P = 1000$ Pa, the value of Q_C is approximated by

$$
Q_{\rm C} = 0.89(VD)^{0.61} \Delta P_{\rm C} \times 10^{-3}.
$$
 (2.12)

 $Q_{\rm C}=0.89(VD)^{0.61}\Delta P_{\rm C}\times10^{-3}.$ In addition to the above, heat will be dissipated due to melting of snow;

heat will be dissipated due to melting of snow;
\n
$$
Q_{\rm F} = \alpha (1 - \gamma) \beta P N L_{\rm F} D,
$$
\n(2.13)

 $Q_{\rm F} = \alpha (1 - \gamma) \beta P N L_{\rm F} D,$ (2.13)
where $Q_{\rm F}$ is the heat loss due to melting of snow (W cm⁻¹), α is the accretion
efficiency (portion of snow contributing to accretion in the amount of snow passing where Q_F is the heat loss due to melting of snow $(W \text{ cm}^{-1})$, α is the accretion
efficiency (portion of snow contributing to accretion in the amount of snow passing
around wire or accreted snow (discussed in later se where Q_F is the heat loss due to melting of snow $(W \text{ cm}^{-1})$, α is the accretion
efficiency (portion of snow contributing to accretion in the amount of snow passing
around wire or accreted snow (discussed in later se efficiency (portion of snow contributing to accretion in the amount of snow passing
around wire or accreted snow (discussed in later sections)), γ is the portion of liquid
water in snowflakes, β is the portion of me around wire or accreted snow (discussed in later sections)), γ is the portion of liquid water in snowflakes, β is the portion of melted snow in accreted snow, P_n is the amount of snow accreted during unit time (di water in snowflakes, β is the portion of melted snow ir
amount of snow accreted during unit time (discussed in
and L_F is the latent heat of fusion (equal to 335 J g⁻¹).
There are other effects which may contribute and L_F is the latent heat of fusion (equal to 335 J g⁻¹). nount of snow accreted during unit time (discussed in a later section, see (3.2)),
d L_F is the latent heat of fusion (equal to 335 J g⁻¹).
There are other effects which may contribute to the heat balance, such as heat

and L_F is the latent heat of fusion (equal to 335 J g^{-1}).
There are other effects which may contribute to the heat balance, such as heat radiated from surface of the accreted snow and solar radiation, but these are n There are other effects which may con
ated from surface of the accreted snow
during the growth of the snow sleeve. *Phil. Trans. R. Soc. Lond.* A (2000)

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The heat balance on the surface of the wire or accreted snow is now approximated by $Q_{\rm A} + Q_{\rm J} - Q_{\rm F} + Q_{\rm E} = 0.$ (2.14)

$$
Q_{\rm A} + Q_{\rm J} - Q_{\rm F} + Q_{\rm E} = 0. \tag{2.14}
$$

 $Q_{\rm A} + Q_{\rm J} - Q_{\rm F} + Q_{\rm E} = 0.$ (2.14)
When applied to practical cases, the current required to prevent or melt accreted
ow can be deduced from the heat balance (see the theoretical model of Admirat When applied to practical cases, the current required to prevent or melt accreted
snow can be deduced from the heat balance (see the theoretical model of Admirat
et al. (1988a)) snow can be deduced from the heat balance (see the theoretical model of Admirat *et al.* (1988*a*)).

In this context, it should be noted that the current required to prevent snow accretion is much smaller than that needed to melt the snow. der than that needed to melt the snow.
3. Estimation of wet-snow load

(*a*) *History and background*

 (a) *History and background*
Although snow accretion on overhead wires can occur under a wide range of meteorological conditions, the occurrence of heavy overload is confined to wet snow falling Although snow accretion on overhead wires can occur under a wide range of meteo-
rological conditions, the occurrence of heavy overload is confined to wet snow falling
in a positive air temperature. In establishing appropr rological conditions, the occurrence of heavy overload is confined to wet snow falling
in a positive air temperature. In establishing appropriate design load of overhead
lines, the ice (snow) load, having a certain long re in a positive air temperaturelines, the ice (snow) load, hand used (see IEC 1991).
Such research on design lines, the ice (snow) load, having a certain long return period, should be determined
and used (see IEC 1991).
Such research on design overloads continues in France, Norway, Iceland and the

and used (see IEC 1991).

Such research on design overloads continues in France, Norway, Iceland and the

UK, etc. (see Ford 1986; Admirat *et al.* 1988*;* Baldit *et al.* 1988; Finstad *et al.* 1990;

Makkonen & Ahti 1993 Such research on design overloads continues in France, Norway, Iceland and the UK, etc. (see Ford 1986; Admirat *et al.* 1988*;* Baldit *et al.* 1988; Finstad *et al.* 1990; Makkonen & Ahti 1993; Kiessling & Ruhnau 1993; UK, etc. (see Ford 1986; Admirat *et al.* 1988*b*; Balc Makkonen & Ahti 1993; Kiessling & Ruhnau 1993; Krishnasamy & Fikke 1998; Yukino *et al.* 1998). In the early stages of such work in Japan it was Makkonen & Ahti 1993; Kiessling & Ruhnau 1993; Eliasson & Thorsteins 1993, 1996;
Krishnasamy & Fikke 1998; Yukino *et al.* 1998).
In the early stages of such work in Japan, it was assumed that wet-snow accretion

Krishnasamy & Fikke 1998; Yukino *et al.* 1998).
In the early stages of such work in Japan, it was assumed that wet-snow accretion
only occurred at low wind, as previously noted. Shoda (1953) proposed a method for
estimat In the early stages of such work in Japan, it was assumed that wet-snow accretion
only occurred at low wind, as previously noted. Shoda (1953) proposed a method for
estimating wet-snow load on communication lines, based on only occurred at low wind, as previously noted. Shoda (1953) proposed a method for estimating wet-snow load on communication lines, based on his observations and the assumption that all of the fallen snow passing within th estimating wet-snow load on communication lines, based on his observations and the assumption that all of the fallen snow passing within the horizontal projected area of the accreted snow (initially that of wire) will cont assumption that all of the fallen snow passing within the horizontal projected area
of the accreted snow (initially that of wire) will contribute and accrete on the wire
as a cylindrical sleeve. The relationship between th of the accreted snow (initially that of wire) will contribute and accrete on the wir
as a cylindrical sleeve. The relationship between the diameter of the snow sleeve and
the depth of new-fallen snow based on the above ass as a cylindrical sleeve. The relationship between the diameter of the snow sleeve and the depth of new-fallen snow based on the above assumptions is given as follows:

$$
D_{\rm S} = N/\pi,\tag{3.1}
$$

 $D_{\rm S} = N/\pi$, (3.1)
where $D_{\rm S}$ is the diameter of snow accreted on the wire (cm) and N is the depth
of fallen snow (cm). In figure 8 the results and those predicted by (3.1) are dis- $D_S = N/m$,
where D_S is the diameter of snow accreted on the wire (cm) and N is the depth
of fallen snow (cm). In figure 8 the results and those predicted by (3.1) are dis-
played Based on this relationship it is now possi where D_S is the diameter of snow accreted on the wire (cm) and N is the depth
of fallen snow (cm). In figure 8 the results and those predicted by (3.1) are dis-
played. Based on this relationship, it is now possible to of fallen snow (cm). In figure 8 the results and those predicted by (3.1) are dis-
played. Based on this relationship, it is now possible to calculate, in a simple man-
ner, the diameter of the snow sleeve once the amou played. Based on this relationship, it is now possible to calculate, in a simple man-
ner, the diameter of the snow sleeve once the amount of fallen snow accumulated is
known. Shoda (1953) also proposed to calculate the m ner, the diameter of the snow sleeve once the amount of fallen snow accumulated is
known. Shoda (1953) also proposed to calculate the mass of snow using a density
of 100 kg m⁻³, since his observations were limited to lo known. Shoda (1953) also proposed to calculate the mass of snow using a density
of 100 kg m⁻³, since his observations were limited to low wind speeds. In fact, he
assumed that the density of the accreted snow was the sa 100 kg m^{-3} , since his observations were limited to low wind speeds. In fact, he sumed that the density of the accreted snow was the same as the new-fallen snow.
Based on his observations, he also concluded that, for l

assumed that the density of the accreted snow was the same as the new-fallen snow.
Based on his observations, he also concluded that, for large wires, growth to a cylindrical sleeve shape was less probable than in the case Based on his observations, he also concluded that, for large wires, growth to a cylindrical sleeve shape was less probable than in the case of small solid wire. This is because, for large wires, it takes longer for cylindr cylindrical sleeve shape was less probable than in the case of small solid wire. This is
because, for large wires, it takes longer for cylindrical-sleeve growth and, during this
time, the possibility of spontaneous sheddin because, for large wires, it takes longer for cylindrical-sleeve growth and, during this
time, the possibility of spontaneous shedding is much higher. In further experiments
to be discussed later, the growing process will time, the possibility of spontaneous shedding is much higher. In further experiments
to be discussed later, the growing process will be significantly different between the
stranded wire usually used on power lines and the to be discussed later, the growing process will be significantly different between the stranded wire usually used on power lines and the solid wire used for communication lines. In particular, the calculated results based stranded wire usually used on power lines and the solid wire used for communication
lines. In particular, the calculated results based on Shoda's method are a conservative
estimate of snow load during low wind speed and ir lines. In particular, the calculated results based on Shoda's method are a conservative
estimate of snow load during low wind speed and irrespective of air temperature (as
shown in figure 3 (solid line)). To this author's estimate of snow load during low wind speed and irrespective of air temperature (as shown in figure 3 (solid line)). To this author's knowledge, the above is the earliest study of snow accretion undertaken in Japan.

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Snowaccretiononoverhead wires ²⁹⁵³ Downloaded from rsta.royalsocietypublishing.org

8. Relationship between depth of newly fallen snow (N) and diame accreted snow (D_S) . $\bar{\theta}_a$ is ambient temperature during accretion.

accreted snow (D_s) . θ_a is ambient temperature during accretion.
Since the Japanese utilities experienced severe damage to their power lines, includ-Since the Japanese utilities experienced severe damage to their power lines, includ-
ing many tower collapses, in 1963, 1972 and 1981, a great deal of research has been
undertaken to understand wet-snow accretion and to de Since the Japanese utilities experienced severe damage to their power lines, includ-
ing many tower collapses, in 1963, 1972 and 1981, a great deal of research has been
undertaken to understand wet-snow accretion and to de ing many tower collapses, in 1963, 1972 and 1981, a great deal of research has been
undertaken to understand wet-snow accretion and to develop methods for estimates
for snow load on power lines. Methods for decreasing snow undertaken to understand wet-snow accretion and to develop methods for estimates for snow load on power lines. Methods for decreasing snow loads on wires has also been done by all utilities and associated organizations suc

As mentioned previously, the author is unaware of any satisfactory physical model been done by all utilities and associated organizations such as CRIEPI.
As mentioned previously, the author is unaware of any satisfactory physical model
of snow accretion. Many problems remain to be solved and research ef As mentioned previously, the author is unaware of any satisfactory physical model
of snow accretion. Many problems remain to be solved and research efforts continue
in many countries. In the following sections, results so of snow accretion. Many problems remain to be solved and research efforts continue in many countries. In the following sections, results so far obtained will be briefly described in the hope that this is useful in avoiding

(*b*) *Wet-snow accretion on wires under windy conditions and*
(*b*) *Wet-snow accretion on wires under windy conditions and the cylindrical-sleeve model*

the cylindrical-sleeve model
Shoda's (1953) study dealt mainly with snow accretion at low wind speeds. As μ above, the utilities of Japan experienced severe damages to power lines
under conditions where wind action could not be neglected. Thus Sakamoto & Ishi-Shoda's (1953) study dealt mainly with snow accretion at low wind speeds. As
described above, the utilities of Japan experienced severe damages to power lines
under conditions where wind action could not be neglected. Thu described above, the utilities of Japan experienced severe damages to power lines
under conditions where wind action could not be neglected. Thus Sakamoto & Ishi-
hara (1984) developed a new method based on the use of the under conditions where wind action could not be neglected. Thus Sakamoto & Ishihara (1984) developed a new method based on the use of the cylindrical-sleeve model.
That is, when wind action is taken into account, the valu hara (1984) developed a new method based on the use of the cylindrical-sleeve model.
That is, when wind action is taken into account, the value of the snow precipitation intensity P_n is approximated by

d by
\n
$$
P_n = P\sqrt{1 + (V\sin\theta/V_N)^2},
$$
\n(3.2)

 $P_n = P\sqrt{1 + (V\sin\theta/V_N)^2}$, (3)
where P is the intensity of precipitation observed on ground surface (g cm⁻² s⁻
V is the wind speed (cm s⁻¹) V_y is the falling speed of snowflake (cm s⁻¹) and f s^{-1}), where P is the intensity of precipitation observed on ground surface $(g \text{ cm}^{-2} \text{ s}^{-1})$,
V is the wind speed (cm s^{-1}) , V_N is the falling speed of snowflake (cm s^{-1}) , and θ is
the angle between the axes of wire where P is the intensity of precipitation observed on gr V is the wind speed (cm s^{-1}) , V_N is the falling speed of s the angle between the axes of wire and wind direction. *Phil. Trans. R. Soc. Lond.* A (2000) *Phil. Trans. R. Soc. Lond.* A (2000)

²⁹⁵⁴ *Y. Sakamoto* Downloaded from rsta.royalsocietypublishing.org

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Now, if it is assumed that the amount of snow accreted on the wire is P_n multiplied Now, if it is assumed that the amount of snow accreted on the wire is P_n multiplied
by α (where α is an accretion factor), and that the snow accreted on the wire is
cylindrical in shape, it follows that Now, if it is assumed that the amous
by α (where α is an accretion factor
cylindrical in shape, it follows that that
 $2\pi R \rho_S dR = \alpha P_n 2R dt,$ (3.3)

$$
2\pi R\rho_{\rm S} \, \mathrm{d}R = \alpha P_n 2R \, \mathrm{d}t,\tag{3.3}
$$

where R is the radius of accreted snow (cm) (radius of wire $+$ thickness of accreted where R is the radius of accreted snow (cm) (radius of wire + thickness of accreted
snow = $R_0 + r$), ρ_S is the density of accreted snow (g cm⁻³), t is the time (s), r is
the thickness of accreted snow (cm), and R_0 where R is the radius of accreted snow (cm) (radius of wire + thickness of as
snow = $R_0 + r$), ρ_s is the density of accreted snow (g cm⁻³), t is the time (
the thickness of accreted snow (cm), and R_0 is the radius $ow = R_0 + r$, ρ_s is the density of a
e thickness of accreted snow (cm), ar
The sleeve thickness now becomes

), and
$$
R_0
$$
 is the radius of the wire (cm).
\n
$$
dR = \frac{\alpha P_n}{\pi \rho_S} dt
$$
\n(3.4)

 $dR = \frac{dR}{\pi \rho_S} dt$
and the mass of snow accreted, dW , per unit length of wire is

dW, per unit length of wire is
\n
$$
dW = 2\pi R \rho_S dR,
$$
\n(3.5)

dl
where W is measured in $g \text{ cm}^{-1}$.
Integrating (3.4) and introducing .

Integrating (3.4) and introducing initial conditions yields

$$
R - R_0 = t = \int_0^t \frac{\alpha}{\pi \rho_S} P_n dt = \frac{\bar{\alpha}}{\pi \bar{\rho}_S} \bar{P}_n t,
$$
\n(3.6)

where the bar denotes average value of quantities taken over a time interval of accretion.

The outer diameter of the snow sleeve is $D = 2(R_0 + t)$ and, using (3.6), it follows that

$$
D = \frac{2\bar{\alpha}}{\phi\bar{\rho}_\mathcal{S}}\bar{P}_n t + D_0.
$$
\n(3.7)

 $D = \frac{2\pi}{\phi \overline{\rho}_S} P_n t + D_0.$
The mass of snow accreted is given, on integration of (3.5), as

$$
W = \int_{R_0}^{R} 2\pi R \bar{\rho}_S dR = \pi \bar{\rho}_S (R^2 - R_0^2)
$$
 (3.8)

 $W = \int_{R_0} 2\pi R \bar{\rho}_S dR = \pi \bar{\rho}_S (R^2 - R_0^2)$ (3.8)
and, on using (3.6), it follows that during cylindrical growth the mass of snow
accreted is given by and, on using (3.6) , it
accreted is given by

$$
W = \frac{\bar{\alpha}^2 \bar{P}_n^2 t^2}{\alpha \bar{\rho}_S} + D_0 \bar{\alpha} \bar{P}_n t.
$$
\n(3.9)

Although this equation is based on the use of mean values of α , P_n and ρ_s , it is Although this equation is based on the use of mean values of α , P_n and ρ_s , it is
possible to divide one event of accretion into subsequences and calculate the mass
of snow for each subsequence using representative Although this equation is based on the use of mean values of α , P_n and ρ_s , it is possible to divide one event of accretion into subsequences and calculate the mass of snow for each subsequence using representative possible to divide one event of accretion in
of snow for each subsequence using represe
when they change significantly with time.
In this equation the quantities P_n and t a In this equation, the quantities P_n and t are known or can be estimated if synoptic In this equation, the quantities P_n and t are known or can be estimated if synoptic

when they change significantly with time.
In this equation, the quantities P_n and t are known or can be estimated if synoptic
meteorological parameters are available and, of course, the diameter of the wire D_0
is kno In this equation, the quantities P_n and t are known or can be estimated if synoptic meteorological parameters are available and, of course, the diameter of the wire D_0 is known. However, the quantities ρ_S and $\$ meteorological parameteorological parameters
from available data.
When this model y known. However, the quantities ρ_S and α are unknown and have to be estimated
om available data.
When this model was proposed, few data were available for deriving empirical
lationship for ρ_S and α and this ind

from available data.
When this model was proposed, few data were available for deriving empirical
relationship for ρ_S and α , and this indicated a need for further experimental and
observational research to make the When this model was proposed, few data were available for deriving empirical relationship for ρ_S and α , and this indicated a need for further experimental and observational research to make the model useful from a p relationship for ρ_S and
observational research to
work is now discussed.

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Snowaccretiononoverhead wires ²⁹⁵⁵

If a wind-tunnel facility designed for productunder controlled atomospheric conditions.

- *c*) *Determination of the dependence of the density of snow sleeve ρ*_S *and accretion*
cfficiency α *cm mateoralogical narameters weing wind tunnal focilities* r *emination of the dependence of the density of snow sleeve* ρ _S and accretive fficiency α *on meteorological parameters using wind-tunnel facilities* $efficient \alpha$ *on meteorological parameters using wind-tunnel facilities*
(i) *Purpose of experiments and facilities employed in the study of wet-snow*
- *accretion*

Although, as will be discussed later, artificial wet-snow accretion experiments have Although, as will be discussed later, artificial wet-snow accretion experiments have
some important drawbacks in simulating natural wet-snow accretion, it is a useful
tool for obtaining the qualitative dependence of wet-sn Although, as will be discussed later, artificial wet-snow accretion experiments have
some important drawbacks in simulating natural wet-snow accretion, it is a useful
tool for obtaining the qualitative dependence of wet-sn tool for obtaining the qualitative dependence of wet-snow accretion on various meteorological parameters. of for obtaining the qualitative dependence of wet-snow accretion on various mete-
ological parameters.
Of course, observations of natural snow accretion carried out in the field are ideal.
wever in Japan, occurrences of h

orological parameters.
Of course, observations of natural snow accretion carried out in the field are ideal.
However, in Japan, occurrences of heavy snow load at specific locations may be few;
note also that the installati Of course, observations of natural snow accretion carried out in the field are ideal.
However, in Japan, occurrences of heavy snow load at specific locations may be few;
note also that the installation of test spans and su However, in Japan, occurrences of heavy snow load at specific locations may be few;
note also that the installation of test spans and supporting equipment for measuring
mass and density, as well as meteorological paramete mass and density, as well as meteorological parameters, is prohibitively expensive. Consequently, it was decided to construct empirical models for estimating ρ_s and α based on the limited results of measurements of natural cases. Such results contain some uncertainties and apply to a relatively nar Consequently, it was decided to construct empirical models for estimating ρ_S and α based on the limited results of measurements of natural cases. Such results contain some uncertainties and apply to a relatively nar based on the limited results of measurements of natural cases. Such results of some uncertainties and apply to a relatively narrow range of parameters, at these reasons they are augmented with results of wind-tunnel experi these reasons they are augmented with results of wind-tunnel experiments.
The wind-tunnel facility used for artificial wet-snow accretion experiments is shown

these reasons they are augmented with results of wind-tunnel experiments.
The wind-tunnel facility used for artificial wet-snow accretion experiments is shown
in figure 9. The facility consists of a blower for generating w The wind-tunnel facility used for artificial wet-snow accretion experiments is shown
in figure 9. The facility consists of a blower for generating wind (wind speed vari-
able continuously), a rotating cylinder with many pr in figure 9. The facility consists of a blower for generating wind (wind speed variable continuously), a rotating cylinder with many protrusions with which small pieces of snow may be scratched off from a mass of sample sn able continuously), a rotating cylinder with many protrusions with which small
pieces of snow may be scratched off from a mass of sample snow and fed into
the airstream, a horizontal conveyor belt for carrying snow samples pieces of snow may be scratched off from a mass of sample snow and fed into
the airstream, a horizontal conveyor belt for carrying snow samples to the rotat-
ing cylinder, and wire samplers for capturing snowflakes blown o the airstream, a horizontal conveyor belt for carrying snow samples to the rotating cylinder, and wire samplers for capturing snowflakes blown off from the outlet of the tunnel. The length of the wire samplers was 2 m, and ing cylinder, and wire samplers for capturing snowflakes blown off from the outlet
of the tunnel. The length of the wire samplers was 2 m, and torsional springs were
attached on each end for simulating torsional rigidity o of the tunnel. The length of the wire samplers was 2 m, and torsional springs were
attached on each end for simulating torsional rigidity of the centre portion of wire
spans with varying span length. The facility was insta attached on each end for simulating torsional rigidity of the centre portion of wire
spans with varying span length. The facility was installed in a hut in which the
temperature could be controlled and kept relatively cons spans with varying span length. The facility was installed in a hut in which the temperature could be controlled and kept relatively constant. Snowfall intensity was simulated by changing the amount of the snow sample carr conveyor.

**MATHEMATICAL,
PHYSICAL**
& ENGINEERING
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PHILOSOPHICAL THE ROYAL

 $Y. Sakamoto$
Just prior to and after each experiment, the amount of snow passing around the Just prior to and after each experiment, the amount of snow passing around the wire sample (P_n) was measured using a specially designed capturing box with a heater. Each end of the wire sampler was supported via load cel Just prior to and after each experiment, the amount of snow passing around the wire sample (P_n) was measured using a specially designed capturing box with a heater. Each end of the wire sampler was supported via load cel wire sample (P_n) was measured using a specially designed capturing box with a heater. Each end of the wire sampler was supported via load cells and the increase in mass of accreted snow was recorded automatically. Rotati heater. Each end of the wire sampler was supported via load cells and the increase
in mass of accreted snow was recorded automatically. Rotation of wire samples with
eccentric growth of accreted snow was measured with a po recorded. centric growth of accreted snow was measured with a potentiometer and also
corded.
In addition, the density and liquid-water content of the accreted snow and sample
ow were measured by weighing samples removed by a small-s

recorded.
In addition, the density and liquid-water content of the accreted snow and sample
snow were measured by weighing samples removed by a small-size sampler and by
use of a calorimeter respectively In addition, the density and liqui
snow were measured by weighing s
use of a calorimeter, respectively.
In the experiments several met In the experiments, several methods for obtaining 'wet snow' as realistically as
In the experiments, several methods for obtaining 'wet snow' as realistically as

use of a calorimeter, respectively.
In the experiments, several methods for obtaining 'wet snow' as realistically as
possible were employed. For example, methods for injecting a water spray simulta-
neously with the snow s In the experiments, several methods for obtaining 'wet snow' as realistically as
possible were employed. For example, methods for injecting a water spray simulta-
neously with the snow sample and the heating of the snow sa possible were employed. For example, methods for injecting a water spray simultaneously with the snow sample and the heating of the snow sample using infrared lamps were tried. In the former method, it was verified that th neously with the snow sample and the heating of the snow sample using infrared
lamps were tried. In the former method, it was verified that the water droplets
injected into the airstream were blown off from the outlet sepa lamps were tried. In the former method, it was verified that the water droplets
injected into the airstream were blown off from the outlet separately, and in the
latter method it proved difficult to heat the snow sample ev injected into the airstream were blown off from the outlet separately, and in the latter method it proved difficult to heat the snow sample evenly. Consequently, both of these methods were unacceptable. Finally, the techni latter method it proved difficult to heat the snow sample evenly. Consequently, both
of these methods were unacceptable. Finally, the technique of lowering the speed of
the conveyor belt carrying the snow samples was used, of these methods were unacceptable. Finally, the technique of lowering the speed of the conveyor belt carrying the snow samples was used, based on the inspection of microscopic photographs of snowflakes collected at the ou Experiments were conducted using fresh snow samples was used, based on the inspection of icroscopic photographs of snowflakes collected at the outlet of the wind-tunnel.
Experiments were conducted using fresh snow samples

microscopic photographs of snowflakes collected at the outlet of the wind-tunnel.
Experiments were conducted using fresh snow samples that had not experienced
positive air temperature, solar radiation or rain after accumul Indeed, it was verified that results of the experiments differed significantly on using fresh or metamorphosed snow. positive air temperature, solar radiation or rain after accumulation on the snow cover.

Experiments were carried out corresponding to a number of combinations of parameter ranges expected to occur in natural conditions.

In addition, the influence of Joule heat on the snow accretion was investigated ameter ranges expected to occur in natural conditions.
In addition, the influence of Joule heat on the snow accretion was investigated
yielding data on the lower limit of current necessary for preventing snow accretion
and In addition, the influence of Joule heat
yielding data on the lower limit of current
and melting of the accreted snow sleeve.
The experiments were carried out as and melting of the accreted snow sleeve.
The experiments were carried out as cooperative work between Electricité de

France and CRIEPI for three winters.

(ii) *Density of accreted snow*

The results of experiments were analysed using the method of multiple regression
alysis, taking density as the criterion variable and meteorological parameters as The results of experiments were analysed using the method of multiple regression
analysis, taking density as the criterion variable and meteorological parameters as
the functional variables to vield the qualitative depend The results of experiments were analysed using the method of multiple regression
analysis, taking density as the criterion variable and meteorological parameters as
the functional variables, to yield the qualitative depend analysis, taking density as the criterion variable and meteorological parameters as
the functional variables, to yield the qualitative dependence of wet-snow accretion
characteristics on meteorological parameters. The foll the functional variables, to yield the qualitative dependence of wet-snow accretion density of accreted snow as a function of the main parameters, was obtained:

$$
\rho_{\rm S} = 0.671V - 0.0103V^{1.1} + 0.0574T - 0.0107P_n - 0.048,\tag{3.10}
$$

 $\rho_{\rm S} = 0.671V - 0.0103V^{1.1} + 0.0574T - 0.0107P_n - 0.048,$ (3.10)
where $\rho_{\rm S}$ is the density of accreted snow (g cm⁻³), V is the wind speed (m s⁻¹), is the air temperature (°C) and P_{ri} is the amount of snow pass $), T$ where ρ_S is the density of accreted snow $(g \text{ cm}^{-3})$, V is the wind speed (m s^{-1}) , T is the air temperature (°C), and P_n is the amount of snow passing around the wire per unit time where ρ_S is the
is the air temper
per unit time.
The number α is the air temperature (°C), and P_n is the amount of snow passing around the wire per unit time.
The number of data used for deriving the equation was $n = 106$ and the multiple correlation coefficient was found to be r

per unit time.
The number of data used for deriving the equal correlation coefficient was found to be $r = 0.87$.
Equation (3.10) introduces the second term to a The number of data used for deriving the equation was $n = 106$ and the multiple rrelation coefficient was found to be $r = 0.87$.
Equation (3.10) introduces the second term to avoid overestimation of the density.
ne equati

Equation (3.10) introduces the second term to avoid overestimation of the density.
The equation implies that increasing the wind speed and increasing the temperature Equation (3.10) introduces the second term to avoid overestimation of the density.
The equation implies that increasing the wind speed and increasing the temperature
have the effect of increasing the density. When consi The equation implies that increasing the wind speed and increasing the temperature have the effect of increasing the density. Moreover, increasing the amount of snow fed to the sleeve has the effect of decreasing the densi *Phil. Trans. R. Soc. Lond.* A (2000)

Snowaccretiononoverhead wires ²⁹⁵⁷

density (measured) (g cm⁻³)
Figure 10. Comparison between measured and calculated densities (artificial)
 $(n = 106 \text{ s} - 0.87)$ een measured and calc
 $(n = 106, r = 0.87).$

 $(n = 106, r = 0.87)$.
effect of changing ranges of parameters, it is clear that wind speed is the most effect of changing ranges of parameters, it is clear that wind speed is the most
significant. Since the density of water and ice are almost the same, the density of
the snow sleeve is mainly governed by air contained in th effect of changing ranges of parameters, it is clear that wind speed is the most
significant. Since the density of water and ice are almost the same, the density of
the snow sleeve is mainly governed by air contained in th significant. Since the density of water and ice are almost the same, the density of
the snow sleeve is mainly governed by air contained in the structure and, if the wind
speed is increased, greater compaction will take pla the snow sleeve is mainly governed by air contained in the structure and, if the wind
speed is increased, greater compaction will take place. The density of accreted snow
will, in principle, be at its maximum when the slee speed is increased, greater compaction will take place. The density of accreted snow
will, in principle, be at its maximum when the sleeve consists of liquid water and
metamorphosed ice particles without the inclusion of will, in principle, be at its maximum when the sleeve consists of liquid water and
metamorphosed ice particles without the inclusion of air (see the photographs in
Colbeck & Ackley (1982)). It can lie in the range 0.9–1.0 metamorphosed ice particles without the inclusion of air (see the Colbeck & Ackley (1982)). It can lie in the range $0.9-1.0 \text{ g cm}^{-3}$, have been observed at higher wind speeds (for example, 15 m s^{-1}).
Thus general t have been observed at higher wind speeds (for example, 15 m s^{-1}). blbeck & Ackley (1982)). It can lie in the range $0.9-1.0 \text{ g cm}^{-3}$, and such cases
we been observed at higher wind speeds (for example, 15 m s^{-1}).
Thus general trends expressed in (3.10) are physically acceptable. I

have been observed at higher wind speeds (for example, 15 m s^{-1}).
Thus general trends expressed in (3.10) are physically acceptable. In figure 10,
measured densities during experiments are compared with calculated me measured densities during experiments are compared with calculated measurements using (3.10) .

(iii) *Accretion efficiency*

Since the mass of snowflakes is relatively high, the collision coefficient on a wire will Since the mass of snowflakes is relatively high, the collision coefficient on a wire will
be close to unity for wind speeds higher than, say, 5 m s^{-1} . This fact is shown clearly
in experiments by Eeles *et al.* (1986 Since the mass of snowflakes is relatively high, the collision coefficient on a wire will
be close to unity for wind speeds higher than, say, 5 m s^{-1} . This fact is shown clearly
in experiments by Eeles *et al.* (1986 be close to unity for wind speeds higher than, say, 5 m s^{-1} . This fact is shown clearly
in experiments by Eeles *et al.* (1986), on using a water-tunnel simulation. However,
not all impacted snowflakes on the wire or in experiments by Eeles $et al. (1986)$, on using a water-tunnel simulation. However, not all impacted snowflakes on the wire or snow sleeve necessarily contribute to an increase in the mass of the sleeve. Some of the flakes will rebound and not accrete and some may melt. In addition, although the cylindrical sleeve model is useful from a practical viewpoint, it ignores the effect of the t and some may melt. In addition, although the cylindrical sleeve model is useful from
a practical viewpoint, it ignores the effect of the torsional rigidity of the wires and,
moreover, for practical power lines, the accrete a practical viewpoint, it ignores the effect of the torsional rigidity of the wires and,

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of the torsional rigidity of wire and yielding the shape of accreted snow along the

of the torsional rigidity of wire and yielding the shape of accreted snow along the span, have been developed by Poots (1996). Essentially, these models should be further developed with the aid of empirical models derived **MATHEMATICAL,
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SCIENCES of the torsional rigidity of wire and yielding the shape of accreted snow along the span, have been developed by Poots (1996). Essentially, these models should be further developed with the aid of empirical models derived span, have been developed by Poots (1996). Essentially, these models should be further developed with the aid of empirical models derived from experiments. In the following, the effect of torsional rigidity is assumed to b further developed with the aid of empirical models derived from experiments. In the following, the effect of torsional rigidity is assumed to be included in the observed accretion efficiency. It should also be emphasized t following, the effect of torsional rigidity is assumed to be included in the observed
accretion efficiency. It should also be emphasized that, when taking into account the
effect of torsional rigidity of a wire span, the s THE ROYAL

accretion efficiency. It should also be emphasized that, when taking into account the effect of torsional rigidity of a wire span, the so-called accretion efficiency must also be a function of material, stranding and size effect of torsional rigidity of a wire span, the so-called accretion efficiency must also
be a function of material, stranding and size of the wire, as well as the span length
and locations along the span. In many cases it has been observed that snow accreted on a wire can be shed and locations along the span.
In many cases it has been observed that snow accreted on a wire can be shed
spontaneously. This phenomenon is important in making a realistic estimate of snow
load but, unfortunately conditio In many cases it has been observed that snow accreted on a wire can be shed
spontaneously. This phenomenon is important in making a realistic estimate of snow
load but, unfortunately, conditions and mechanisms for shedding spontaneously. This phenomenon is important in making a realistic estimate of snow
load but, unfortunately, conditions and mechanisms for shedding are as yet not fully
understood. It must be emphasized that the accretion e load but, unfortunately, conditions and mechanisms for shedding are as yet not fully understood. It must be emphasized that the accretion efficiency used in practice ignores shedding and this could be critical in estimatin overload.

nores shedding and this could be critical in estimating the possible maximum snow
erload.
From results of artificial accretion experiments in which cylindrical sleeves formed
e accretion, efficiency was deduced from the me overload.
From results of artificial accretion experiments in which cylindrical sleeves formed
the accretion, efficiency was deduced from the measured mass of the sleeve and the
density using (3.9) Multiple regression t From results of artificial accretion experiments in which cylindrical sleeves formed
the accretion, efficiency was deduced from the measured mass of the sleeve and the
density using (3.9). Multiple regression techniques we the accretion, efficiency was deduced from the measured mass of the sleeve and the density using (3.9). Multiple regression techniques were also completed, with the accretion efficiency taken as the criterion variable and density using (3.9). Multiple regression techniques were also completed, with the accretion efficiency taken as the criterion variable and meteorological parameters as functional variables. The following equation expresses accretion efficiency taken as the criterion variable and meteorological parameters as functional variables. The following equation expresses the accretion efficiency as a function of the basic parameters: $\alpha = 0.624 \exp\{-0.0865(T - 3.27)^2\} \times \exp\{0.0621V - 0.744P_n\}.$ (3.11)

$$
\alpha = 0.624 \exp\{-0.0865(T - 3.27)^2\} \times \exp\{0.0621V - 0.744P_n\}.
$$
 (3.11)

Here, the same notation is used as in (3.10). The number of data used for analysis Here, the same notation is used as in (3.10). The number of data used for analysis was $n = 52$, with the multiple correlation coefficient $r = 0.84$. The reason that the data used here were fewer than in the study of densi Here, the same notation is used as in (3.10). The number of data used for analysis was $n = 52$, with the multiple correlation coefficient $r = 0.84$. The reason that the data used here were fewer than in the study of densi was $n = 52$, with the mult
data used here were fewer t
involving snow shedding.
This equation implies the data used here were fewer than in the study of density is due to the rejection of data
involving snow shedding.
This equation implies that the accretion efficiency has a maximum at $T = 3.27$,

but this value is expected to overestimate the real values. This equation implies that the accretion efficiency has a maximum at $T = 3.27$,
it this value is expected to overestimate the real values.
From a physical viewpoint, it is suspected that when the air temperature decreased

but this value is expected to overestimate the real values.
From a physical viewpoint, it is suspected that when the air temperature decreased
close to freezing, the liquid-water content which aids the sticking process dec From a physical viewpoint, it is suspected that when the air temperature decreased
close to freezing, the liquid-water content which aids the sticking process decreased
and flakes tended to rebound; when temperature increa close to freezing, the liquid-water content which aids the sticking process decreased
and flakes tended to rebound; when temperature increased above the critical value,
the heat flux induced by wind convection melted much

The wind speed may have several effects on the accretion efficiency (for example, the heat flux induced by wind convection melted much of the snow.
The wind speed may have several effects on the accretion efficiency (for example,
the change in snowflake trajectories, the collision speed on the sleeve, t The wind speed may have several effects on the accretion efficiency (for example, the change in snowflake trajectories, the collision speed on the sleeve, the change in heat flux), but to date the predominate effect has no the change in snowflake trajectories, the collision speed on the sleeve, the change in heat flux), but to date the predominate effect has not been isolated. In figure 11, a comparison is given between calculated and obser heat flux), but to date the predominate effect has not been isolated. In figure 11, a comparison is given between calculated and observed values for the accretion efficiency (regarding the latter, see Tachizaki *et al*. (1 a comparison is given between calculated and observed values for the accretion effi-

ciency (regarding the latter, see Tachizaki *et al.* (1988)).
In addition, the effects of the liquid-water content of the snow sleeve and that for
the load current were investigated and analysed, but these results are not In addition, the load curren
in this paper. (iv) *Defects of artificial experiments (lack of equivalency with natural cases)*

As previously pointed out in Sakamoto *et al.* (1988*a*), although artificial accretion As previously pointed out in Sakamoto *et al.* (1988*a*), although artificial accretion experiments are a useful tool in understanding the role of the various parameters in the snow accretion phenomenon it does not give t As previously pointed out in Sakamoto *et al.* (1988*a*), although artificial accretion experiments are a useful tool in understanding the role of the various parameters in the snow accretion phenomenon, it does not give experiments are a useful tool in understanding the role of the various parameters in
the snow accretion phenomenon, it does not give the complete picture. First of all,
it should be pointed out that there is a real difficu the snow accretion phenomenon, it does not give the complete picture. First of all, it should be pointed out that there is a real difficulty in reproducing the relationship between the liquid-water content of snowflakes an

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Figure 11. Comparison between measured and calculated accretion efficiencies (artificial)
 $(n = 52 \ r = 0.84)$ asured and calculate $(n = 52, r = 0.84)$.

 $(n = 52, r = 0.84)$.
conditions. In a natural snowfall, snowflakes may travel a relatively long time through
a positive temperature air layer in which the surface temperature is above freezing conditions. In a natural snowfall, snowflakes may travel a relatively long time through
a positive temperature air layer in which the surface temperature is above freezing.
However in the case of artificially generated 'we conditions. In a natural snowfall, snowflakes may travel a relatively long time through
a positive temperature air layer in which the surface temperature is above freezing.
However, in the case of artificially generated 'w a positive temperature air layer in which the surface temperature is above freezing.
However, in the case of artificially generated 'wet snow', much less time is available
for heat exchange with the surrounding air. Attemp for heat exchange with the surrounding air. Attempts were made to lengthen the for heat exchange with the surrounding air. Attempts were made to lengthen the time prior to accretion on the wire sample but in practice it was difficult to do so; snow samples sticking everywhere on the facility, with in time prior to accretion on the wire sample but in practice it was difficult to do
so; snow samples sticking everywhere on the facility, with increasing deficiencies in
experimentation. Clearly, the liquid-water content of so; snow samples sticking everywhere on the facility, with increasing deficiencies is
experimentation. Clearly, the liquid-water content of 'wet snow' under experiments
conditions was suspected to be less than natural valu experimentation. Clearly, the liquid-water content of 'wet snow' under experimental conditions was suspected to be less than natural value at the same temperature.

Regarding questions of equivalency between conditions in the artificial experiments agreement can be established.
The difficulties involved are summarized as follows. and the natural observations, further work must be undertaken before quantitative

- The difficulties involved are summarized as follows.
(1) The snowfall intensity selected for experiments was too high compared with
natural values thus shortening the time required in a sequence of the simula-The snowfall intensity selected for experiments was too high compared with natural values, thus shortening the time required in a sequence of the simulation. Consequently, in the experimental work, snow accretion on wire o The snowfall intensity selected for experiments was too high compared with natural values, thus shortening the time required in a sequence of the simulation. Consequently, in the experimental work, snow accretion on wire natural values, thus shortening the time required in a sequence of the simulation. Consequently, in the experimental work, snow accretion on wire occurred for temperatures as high as $4-5^{\circ}\text{C}$, which, under natural co tion. Consequently, in the experimental
for temperatures as high as $4-5$ °C, w
have turned the precipitation to rain.
- have turned the precipitation to rain.

(2) Regarding wind speed, it was possible to reproduce any mean speed, but fluc-

tuations and uneveness in speed with respect to vertical locations within the Regarding wind speed, it was possible to reproduce any mean speed, but fluctuations and uneveness in speed with respect to vertical locations within the test area could not be eliminated Regarding wind speed, it was possibutations and uneveness in speed witest area could not be eliminated.
- test area could not be eliminated.

(3) The relative humidity of air was kept above 80% , but it was thought that this

value was slightly lower than in natural conditions, due to the fact that the The relative humidity of air was kept above 80% , but it was thought that this value was slightly lower than in natural conditions, due to the fact that the temperature within the but had to be kept higher than the outd The relative humidity of air was kept above 80% , but it was thought that this value was slightly lower than in natural conditions, due to the fact that the temperature within the hut had to be kept higher than the outd value was slightly lower than in natural conditions, due to the fact that the temperature within the hut had to be kept higher than the outdoor value so as to obtain 'wet snow'.

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It was concluded that heat exchange under natural conditions was not simulated It was concluded that heat exchange under natural conditions was not simulated exactly, and some caution must be exercised in the use of the above equations for density and accretion efficiency in real situations It was concluded that heat exchange under nature
xactly, and some caution must be exercised in the
density and accretion efficiency in real situations.

(*d*) *Derivation of empirical equations based on data of natural observations*

(d) Derivation of empirical equations based on data of natural observations
During the research projects, observations of natural snow accretion were requested
om all utilities in Japan using a unified format for methods During the research projects, observations of natural snow accretion were requested from all utilities in Japan using a unified format for methods for observation and During the research projects, observations of natural snow accretion were requested
from all utilities in Japan using a unified format for methods for observation and
instruments used (see Sakamoto *et al.* 1988b). Measure from all utilities in Japan using a unified format for methods for observation and
instruments used (see Sakamoto *et al.* 1988*b*). Measurements of the mass, density,
shape and liquid-water content of accreted snow, as w instruments used (see Sakamoto *et al.* 1988b). Measurements of the mass, density, shape and liquid-water content of accreted snow, as well as meteorological parameters such as air temperature, humidity, precipitation int shape and liquid-water content of accreted snow, as well as meteorological parameters
such as air temperature, humidity, precipitation intensity, speed and direction of
wind, were obtained. To facilitate this exercise, an such as air temperature, humidity, precipitation intensity, speed and direction of wind, were obtained. To facilitate this exercise, an observation manual including videotape instruction was prepared and distributed, so as wind, were obtained. To facilitate this exercise, an observation manual including videotape instruction was prepared and distributed, so as to avoid errors due to the use of different procedures. Instruments for measuremen videotape instruction was prepared and distributed, so as to avoid errors due to the
use of different procedures. Instruments for measurements were specified in detail.
In particular, a common difficulty was encountered wh use of different procedures. Instruments for measurements were specified in detail.
In particular, a common difficulty was encountered when measuring the diameter of
snow sleeves on energized power lines when observed from In particular, a common difficulty was encountered when measuring the diameter of snow sleeves on energized power lines when observed from the ground surface. For this, a special method using optical instruments with scale show sleeves on energized power lines when observed from the ground surface. For this, a special method using optical instruments with scale and distance meters was developed and specified for use.
Some results about natur is, a special method using optical instruments with scale and distance meters was
veloped and specified for use.
Some results about natural wet-snow events were reported during the project,
cluding results for operating li

including results for operating lines and test spans. Some of the results are summa-Some results about natural wet-snow events were reported during the project, including results for operating lines and test spans. Some of the results are summarized in table 1, in which the observations for numbers $1-41$ including results for operating lines and test spans. Some of the results are summa-
rized in table 1, in which the observations for numbers 1–41 were obtained during
the project and remaining ones were added from historic rized in table 1, in which
the project and remaining
to be relatively reliable.
Since these data were i e project and remaining ones were added from historical records and are thought
be relatively reliable.
Since these data were mainly observed on operating lines, some of the measure-
prise relating to the mass of accreted

to be relatively reliable.
Since these data were mainly observed on operating lines, some of the measure-
ments relating to the mass of accreted snow involved estimation based on sag of
span or direct measurements on short Since these data were mainly observed on operating lines, some of the measurements relating to the mass of accreted snow involved estimation based on sag of span or direct measurements on short lengths of wire located clos ments relating to the mass of accreted snow involved estimation based on sag of span or direct measurements on short lengths of wire located close to line. Some of the data on density were measured after snow events or giv the wires. Thus they include some uncertainty or unavoidable errors, as expected the data on density were measured after snow events or given by samples shed from
the wires. Thus they include some uncertainty or unavoidable errors, as expected
in such kinds of observations. In addition, meteorological the wires. Thus they include some uncertainty or unavoid
in such kinds of observations. In addition, meteorological parameters
were made available from records of nearby observatories.
In table 1 the following notation is were made available from records of nearby observatories.
In table 1, the following notation is employed. V_N are mean values of the normal

were made available from records of nearby observatories.
In table 1, the following notation is employed. V_N are mean values of the normal
components of the wind speed to the line, using 10 min averages. T_D is the int In table 1, the following notation is employed. V_N are mean values of the normal components of the wind speed to the line, using 10 min averages. T_D is the interface air temperature, which determines whether precipita components of the wind speed to the line, using 10 min averages. T_D is the interface
air temperature, which determines whether precipitation is rain or snow. The ratio
of air temperature to T_D was taken because it has air temperature, which determines whether precipitation is rain or snow. The ratio of air temperature to T_D was taken because it has been found that T_D depends of air temperature to T_D was taken because it has been found that T_D depends
on altitude above mean sea level and the synoptic weather system under which
precipitation was experienced, and it was thought that this int on altitude above mean sea level and the synoptic weather system under which
precipitation was experienced, and it was thought that this interface temperature
has an effect on whether the fallen snow is sticky (wet) or no precipitation was experienced, and it was thought that this interface temperature
has an effect on whether the fallen snow is sticky (wet) or not. T_D has been analysed
separately for representative synoptic weather syst has an effect on whether the fallen snow is sticky (wet) or not. T_D has been analysed
separately for representative synoptic weather systems such as monsoon-type and
depression-type. For depression-type, T_D is express separately for representative synoptic weather system depression-type. For depression-type, T_D is expressed mean sea level H (measured in metres) as follows: in metres) as follows:
 $T_{\rm D} = 2.31 - 0.101 \times \ln(H).$ (3.12)

$$
T_{\rm D} = 2.31 - 0.101 \times \ln(H). \tag{3.12}
$$

 $T_{\text{D}} = 2.31 - 0.101 \times \ln(H)$. (3.12)
Furthermore, P is the amount of precipitation water equivalent (measured in mil-
limetres) during wet-snow conditions P, is the amount of snow passing around the Furthermore, P is the amount of precipitation water equivalent (measured in mil-
limetres) during wet-snow conditions, P_n is the amount of snow passing around the
wire (calculated from (3.2) P_t is the product of P_t Furthermore, P is the amount of precipitation water equivalent (measured in mil-
limetres) during wet-snow conditions, P_n is the amount of snow passing around the
wire (calculated from (3.2), $P_n t$ is the product of P_n limetres) during wet-snow conditions, P_n is the amount of snow passing around the wire (calculated from (3.2), $P_n t$ is the product of P_n and the duration time (in hours) of wet snow conditions, and α defines the c wire (calculated from (3.2), $P_n t$ is the product of P_n and the duratiof wet snow conditions, and α defines the calculated values for the efficiency, deduced from density and mass measured using (3.9). *efficiency*, deduced from density and mass measured using (3.9).
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Table 1. Summary of observations of wet-snow accretion on wires under natural conditions

Table 1. *Summary of observations of wet-snow accretion on wires under natural conditions*
umn headings: no., number; ID, identification number of the company; alt., altitude; dia (Abbreviations in the column headings: no., number; ID, identification number of the company; alt., altitude; diam., diameter; wt, weight;
AS. accreted snow: o. accretion rate (calculated). Data extracted from past records AS, accreted snow; α , accretion rate (calculated). Data extracted from past records of faults of power lines. Refer to the text for a detailed α , accretion rate (calculated). Data extracted from past records of faults of power lines. Refer to the text for a detailed
ata.) explanation of the data.)

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 $\begin{array}{ccccccccc} -3 & (m\,s^{-1}) & V_N & T & T/T_D & P & P_n & P_n t & \alpha \ \hline & & & & & & & \ 11 & 0.2 & -0.1 & -0.05 & 1.8 & 1.8 & 4.96 & 0.497 \end{array}$ $\begin{array}{cccccc} -0.1 & -0.05 & 1.8 & 1.8 & 4.96 & 0.497 \\ -1.7 & -0.98 & 1.2 & 2.2 & 2.39 & 0.795 \\ -1.7 & -0.98 & 1.2 & 2.2 & 2.39 & 0.795 \end{array}$ -1.7 -0.98 1.2 2.2 2.39 0.795
 -1.7 -0.98 1.2 2.2 2.39 1.081
 -1.7 -0.98 1.2 2.2 2.39 1.081 -1.7 -0.98 1.2 2.2 2.39 1.081
0.7 0.38 2.5 2.7 9.04 0.628 23 2 80 $19/2/83$ 7.8 3.6 12.0 12.0 0.32 0.4 0.4 0.3 2.5 2.7 9.04 0.628 24 2 3.50 14/3/83 7.8 1.9 10.0 10.0 0.24 0.2
 24 2 350 $14/3/83$ 7.8 1.9 10.0 0.24 0.2 0.2 -1.2 -0.70 2.1 1.8 3.61 0.978 $\begin{array}{cccccc} -1.2 & -0.70 & 2.1 & 1.8 & 3.61 & 0.978 \\ -0.2 & -0.11 & 2.1 & 1.8 & 3.57 & 0.967 \\ -0.2 & -0.11 & 2.1 & 1.8 & 2.57 & 0.967 \end{array}$ $\begin{array}{cccccc} -0.2 & -0.11 & 2.1 & 1.8 & 3.57 & 0.967 \\ 0.6 & 0.29 & 1.8 & 4.8 & 5.77 & 0.680 \\ \textrm{0.6} & \circ & \circ & \cdot & \cdot & \cdot & \cdot & \cdot & 0.680 \\ \end{array}$ 26 2 10 26/12/83 7.8 1.5 7.0 7.0 0.40 4.7 2.7 0.6 0.29 1.8 4.8 5.77 0.680 27 2 40 19/2/83 18.2 (2.2) (7.0 7.0) 0.62 1.8 1.5 0.6 0.32 1.7 3.9 5.41 0.980 28 2 40 19/2/83 10.5 (1.1) (5.0 5.0) 0.62 1.8 1.5 0.6 0.32 1.7 3.9 5.41 0.702 29 2 200 20/2/83 18.2 2.1 8.0 6.0 0.55 0.2 0.1 0.06 3.0 3.2 13.32 0.370
30 2 200 20/2/83 18.2 1.0 6.0 6.0 0.34 0.2 0.1 0.06 3.0 3.2 13.32 0.15
30 2 200 20/2/83 18.2 1.0 6.0 0.34 0.4 0.2 0.1 0.06 3.0 3.2 13.32 0.195 30 2 200 20/2/83 18.2 1.0 6.0 6.0 0.34 0.4 0.2 0.1 0.06 3.0 3.2 13.32 0.195 31 2 60 14/3/83 34.2 0.7 4.7 3.3 (0.85) 0.8 0.6 0.4 0.21 1.7 2.0 3.18 0.624 32 2 10 $14/3/83$ 13.0 0.6 3.6 3.1 (0.87) 0.8 0.6 0.4 0.21 1.7 2.0 3.18 0.878
 33 2 100 $14/3/83$ 18.2 0.7 5.0 4.0 0.49 4.5 4.5 -0.1 -0.05 1.5 7.1 7.83 0.302
 3.18 1.83 0.302 $\begin{array}{cccccc} -0.1 & -0.05 & 1.5 & 7.1 & 7.83 & 0.302 \\ -0.1 & -0.05 & 1.5 & 7.1 & 7.83 & 0.316 \\ -0.1 & -0.5 & 1.5 & 7.1 & 7.83 & 0.316 \end{array}$ $\begin{array}{cccccc} -0.1 & -0.05 & 1.5 & 7.1 & 7.83 & 0.316 \\ -0.2 & -0.11 & 1.6 & 9.5 & 9.35 & 0.218 \\ -0.2 & 0.11 & 0.5 & 0.35 & 0.218 \\ \end{array}$ $\begin{array}{cccccc} -0.2 & -0.11 & 1.6 & 9.5 & 9.35 & 0.218 \\ -0.8 & -0.39 & 1.3 & 4.3 & 17.18 & 0.347 \\ \end{array}$ $\begin{array}{cccccc} -0.8 & -0.39 & 1.3 & 4.3 & 17.18 & 0.347 \\ -0.8 & -0.39 & 1.3 & 4.1 & 16.54 & 0.165 \end{array}$ $\begin{array}{r}\n -0.8 \\
 -0.39 \\
 \hline\n \end{array}$ 1.3 4.1 16.54 0.165 0.497 0.795 0.628 0.978 0.967 0.680 0.980 0.702 0.370 0.195 0.624 0.878 0.302 0.316 0.218 0.347 0.165 1.081 α \mathcal{P}_{n} t 9.04 5.41 5.41 13.32 13.32 3.18 3.18 7.18 16.54 4.96 2.39 2.39 3.61 3.57 5.77 7.83 7.83 9.35 meteorological parameters diam. wt of size of density of \overline{AS} meteorological parameters of wire \overline{AS} AS V P_n 2.2 2.2 2.7 $1.8\,$ 1.8 4.8 3.9 3.9 3.2 3.2 2.0 2.0 $\overline{7.1}$ 9.5 4.3 1.8 2.5 1.8 $\overline{1.1}$ 3.0 3.0 1.7 $\frac{5}{1}$ -1.5 $\frac{6}{1}$ $\ddot{3}$ $\ddot{3}$ 2.1 2.1 $\overline{1.1}$ 1.7 \overline{p} $T/T_{\rm D}$ -0.98 -0.98 0.38 0.29 0.32 -0.05 -0.70 -0.11 0.32 0.06 0.06 -0.05 -0.05 -0.39 -0.39 0.21 0.21 -0.11 -1.7 -1.2 -0.2 -0.2 -0.8 -0.8 -1.7 0.7 0.6 0.6 0.6 0.4 0.4 -0.1 \overline{C} $\overline{0}$ -0.1 -0.1 \overline{L} 20 2 100 11/2/85 16.1 (0.9) (10.0 6.0) (0.2) 1.1 0.2
21 2 280 21/2/85 18.2 (0.6) (6.0 4.0) (0.35) 1.1 0.8
 (0.35) 1.1 0.8 21 2 280 21/2/85 18.2 (0.6) $(6.0$ 4.0) (0.35) 1.1 0.8

22 2 280 21/2/85 18.2 (0.9) $(8.0$ 4.0) (0.4) 1.1 0.8
 (0.4) 1.1 0.8 222 2 280 $21/2/85$ 18.2 (0.9) $(8.0$ 4.0) (0.4) 1.1 0.8
 23 2 80 19/2/83 7.8 3.6 12.0 12.0 0.32 0.4 0.4
 23 2 80 19/2/83 7.8 3.6 12.0 12.0 0.32 0.4 0.4 24 2 350 $14/3/83$ 7.8 1.9 10.0 10.0 0.24 0.2 0.2
 25 2 200 $14/3/83$ 18.2 2.3 12.0 12.0 0.21 0.2 0.2
 25 2 200 $14/3/83$ 18.2 2.3 12.0 12.0 0.21 0.2 25 2 200 $14/3/83$ 18.2 2.3 12.0 12.0 0.21 0.2
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27 2.7 2.7 2.7 2.2 2.3 2.3 7.0 7.0 0.40 33 2 100 14/3/83 18.2 0.7 5.0 4.0 0.49 4.5 4.5
 34 2 100 14/3/83 18.2 0.7 5.0 3.5 0.56 4.5 4.5
 14^{13} /83 18.2 0.7 5.0 3.5 0.56 4.5 4.5 34 2 100 $14/3/83$ 18.2 0.7 5.0 3.5 0.56 4.5 4.5
 35 2 100 $14/3/83$ 18.2 0.5 4.0 3.0 0.63 5.5 5.1
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 36 3 16 $21/2/83$ 22.4 4.7 15.0 13.0 0.31 2.8 2.7
 35 3.5 3.7 36 3 16 $21/2/83$ 22.4 4.7 15.0 13.0 0.31 2.8 2.7
37 3 10 $21/2/83$ 22.4 1.3 8.0 8.0 0.29 2.7 2.5 $37 \quad 3 \quad 10 \quad 21/2/83 \quad 22.4 \quad 1.3 \quad 8.0 \quad 0.29 \quad 2.7 \quad 2.5$ \aleph $0.\overline{8}$ 0.8 0.2 0.2 2.7 1.5 1.5 0.2 0.2 0.6 0.6 4.5 4.5 2.7 2.5 0.4 $\overline{5}.1$ $(g \text{ cm}^{-3}) \text{ (m s}^{-1})$ 7.5 1.8 1.8 0.4 0.4 0.8 0.8 4.5 $\ddot{5}$ 5.5 $\frac{8}{2.7}$ 0.2 0.2 \Box 0.4 \geq Table 1. (*Cont.*) density of alt. date of wire AS AS AS
(m) $(dd/\text{mm}/yy)$ (mm) (kg m^{-1}) (cm) (g cm^{-3}) $\begin{array}{ccc} (-1) & (cm) & (g \ cm^{-3}) \ (10.0 & 6.0) & (0.2) \ (6.0 & 4.0) & (0.35) \end{array}$ (0.85) (0.87) AS 0.32 0.40 0.62 0.62 0.55 0.34 0.49 0.56 (0.4) 0.24 0.21 0.63 0.31 0.29 4.0° 12.0 10.0 0.7 $\overline{7.0}$ $5.0)$ 6.0 6.0 2.0 $3.\overline{3}$ 8.0 $\overline{3}$. $\frac{1}{4}$ 3.5 3.0 13.0 size of AS 12.0 (5.0) 8.0 $6.0\,$ 3.6 (8.0) 2.0 0.7 0.7 4.7 5.0 5.0 4.0 5.0 8.0 0.0 no. ID (m) $(dd/\text{mm}/\text{yy})$ (mm) (kg m⁻¹)
20 2 100 11/2/85 16.1 (0.9)
21 2 280 21/2/85 18.2 (0.6) $\left(\log m^{-1} \right)$ \le of AS (0.9) $2.2)$ (1.1) $3.\overline{6}$ 1.9 $2.\overline{3}$ 1.5 2.1 1.0 $\overline{0}$.7 0.6 0.7 ~ 0 $\ddot{0}$ 7.4 1.3 of wire (mm) diam. 18.2 18.2 $\frac{8}{7}$ 7.8 18.2 $\frac{8}{7}$ 18.2 10.5 18.2 18.2 34.2 13.0 18.2 18.2 18.2 22.4 22.4 16.1 $\frac{dd}{m}$ $\frac{m}{y}$ $14/3/83$ $14/3/83$ 26/12/83 $19/2/83$ $14/3/83$ $14/3/83$ $14/3/83$ $21/2/83$ 19/2/83 14/3/83 21/2/85 $21/2/85$ $19/2/83$ $20/2/83$ $20/2/83$ $14/3/83$ $11/2/85$ $21/2/83$ date $\binom{m}{m}$ \ddot{a} 280 280 $80\,$ 350 200 $\overline{10}$ Θ \triangleq 200 200 $60\,$ $\overline{10}$ 100 100 100 16 $\overline{10}$ $\overline{0}$ \Box a a a a a a a a a a a a a a a \sim $\mathbf{\Omega}$ \sim no. Ω 21 23 24 25 នគននន 31 32 33 \mathfrak{Z} 35 36 57

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 $\begin{array}{ccc} \text{--}^3) & (\text{m s}^{-1}) & \text{V}_{\text{N}} & T & T/T_{\text{D}} & P & P_n & P_n t & \alpha \ \text{2)} & 2.7 & 2.3 & -0.7 & -0.34 & 1.3 & 3.7 & 15.47 & 0.746 \end{array}$ −0.7 −0.34 1.3 3.7 15.47 0.746
−0.7 −0.34 1.3 3.7 15.47 0.641
−0.7 −0.34 1.3 3.7 15.47 0.641 $\begin{array}{cccccc} -0.7 & -0.34 & 1.3 & 3.7 & 15.47 & 0.641 \\ -0.7 & -0.34 & 1.3 & 3.8 & 15.90 & 0.221 \\ -0.7 & -0.34 & 1.3 & 3.8 & 15.90 & 0.221 \end{array}$ $\begin{array}{cccccc} -0.7 & -0.34 & 1.3 & 3.8 & 15.90 & 0.221 \\ -0.7 & -0.34 & 1.3 & 3.8 & 15.90 & 0.486 \\ \end{array}$ $\begin{array}{cccc} -0.7 & -0.34 & 1.3 & 3.8 & 15.90 & 0.486 \\ 0.67 & 0.312 & & & 9.64 & 0.805 \\ 0.67 & 0.312 & & & & 0.64 & 0.805 \\ 0.67 & 0.312 & & & & 0.64 & 0.805 \\ 0.67 & 0.312 & & & & 0.64 & 0.805 \\ 0.67 & 0.312 & & & 0.64 & 0.805 \\ 0.67 & 0.312 & & & 0.64 & 0.805 \\ 0.67 &$ 42 1 5 $2/1/62$ 18.2 5.5 13.5 11.5 0.45 5.7 0.67 0.312 9.64 0.805
43 1 9 $25/2/63$ 18.2 5.5 10 0.67 4.9 0.95 0.455 22.11 0.417
42 1 9 $25/2/63$ 18.2 5.5 10 0.67 4.9 0.95 0.455 22.11 0.417 43 1 9 $25/2/63$ 18.2 5.5 10 0.67 4.9 0.95 0.455 22.11 0.417
44 1 110 1/2/70 22.4 5.8 10 0.78 6.6 1.11 0.605 43.8 0.228
44 1 110 1/2/70 22.4 5.8 10 44 1 110 1/2/70 22.4 5.8 10 0.78 6.6 1.11 0.605 43.8 0.228 45 1 $2 \frac{16}{3}/70$ 18.2 7 8 10 0.7
46 1 70 $27/2/72$ 18.2 5.6 >15 0.32 0.19 0.101 0.39 0.487
46 1 70 $27/2/72$ 18.2 5.6 >15 0.32 0.19 0.101 13.99 0.487 >15 0.32 2.3 0.19 0.101 13.99 0.487
10 0.66 8.3 0.37 0.191 20.15 0.430
12.15 0.430 47 1 40 $28/2/72$ 18.2 5 10 0.66 8.3 0.37 0.191 20.15 0.430
48 1 70 $28/2/72$ 13.0 7.8 15 0.44 2.6 0.34 0.181 14.8 0.615
14.8 0.615 14.8 15 14.2 14.2 14.2 14.2 14.2 14.2 14.3 0.615 48 1 70 $28/2/72$ 13.0 7.8 15 0.44 2.6 0.34 0.181 14.8 0.615
49 1 60 $28/2/72$ 17.5 4.47 >11 0.47 1.1 0.25 0.103 9.36 0.815
49 1 60 $28/2/72$ 17.5 4.47 -2.1 0.47 1.1 0.25 0.103 9.36 0.815 >11 0.47 1.1 0.25 0.103 9.36 0.815 50 1 20 $7/4/76$ 22.4 6 19 15 0.3 0.7 1.8 0.63 0.314 8.33 1.012
51 2 430 $16/1/72$ 25.3 4.9 >12 >0.45 1.81 1.00 0.589 22.79 0.307
52 -20.45 -20.45 -20.45 1.81 1.00 0.589 22.79 0.307 >0.45 1.81 1.00 0.589 22.79 0.307
0.62 4.55 0.54 0.296 9.54 0.978
2.954 0.978 52 2 120 $5/2/75$ 18.2 5.7 11 0.62 4.55 0.54 0.296 9.54 0.978
53 3 20 16/2/68 9.6 3.8 10 0.43 5.01 0.59 0.294 10.46 0.633 53 3 20 $16/2/68$ 9.6 3.8 10 0.43 5.01 0.59 0.294 10.46 0.633
 54 3 30 $15/2/68$ 9.6 2.0 8 0.4 4.06 0.63 0.320 5.92 0.763
 54 5.92 0.763 54 3 30 $15/2/68$ 9.6 2.0 8 0.4 4.06 0.63 0.320 5.92 0.76
 55 3 15 $12/3/69$ 10.5 1.9 6 0.7
 0.7 9.02 0.97 0.476 8.63 0.647 $55 \quad 3 \quad 15 \quad 12/3/69 \quad 10.5 \quad 1.9 \quad 6 \quad 0.7 \quad 9.02 \quad 0.97 \quad 0.476 \quad 8.63 \quad 0.647$ 0.487 0.430 0.615 0.815 1.012 0.307 0.978 0.633 0.763 719.0 0.746 0.486 0.805 0.417 0.228 0.470 0.641 0.221 α $P_n t$ $15.47\,$ $15.90\,$ 5.92 15.47 15.90 9.64 22.11 22.94 13.99 20.15 9.36 8.33 22.79 9.54 10.46 8.63 43.8 14.8 meteorological parameters diam. wt of size of density of \overline{AS} meteorological parameters f wire \overline{AS} P_n 3.7 5.7 3.8 3.8 1.3 1.3 1.3 $1.\overline{3}$ \mathbf{p} T/T_D 0.312 0.455 0.605 0.393 0.103 0.314 0.589 0.296 0.294 0.320 0.476 0.101 0.191 0.181 -0.34 -0.34 -0.34 -0.34 0.19 0.88 0.37 0.67 0.34 0.63 00.1 0.54 0.59 0.63 0.95 Ξ 0.25 0.97 -0.7 -0.7 -0.7 -0.7 \overline{L} 38 3 10 $21/2/83$ 18.35 (11.8) (20.0 18.0) (0.42) 2.7 2.3
39 3 20 $21/2/83$ 18.35 (8.9) (18.0 15.0) (0.42) 2.7 2.3
39 3 20 $21/2/83$ 18.35 (8.9) (18.0 15.0) (0.42) 2.7 2.3 39 3 20 $21/2/83$ 18.35 (8.9) (18.0 15.0) (0.42) 2.7 2.3
40 3 10 $21/2/83$ 13.0 1.7 10.0 7.0 0.30 2.6 2.5
40 3 10 $21/2/83$ 13.0 1.7 10.0 7.0 0.30 2.6 2.5 40 3 10 $21/2/83$ 13.0 1.7 10.0 7.0 0.30 2.6 2.5
41 3 12 $21/2/83$ 13.0 7.2 20.0 15.0 0.30 2.6 2.5
 $\frac{25}{25}$ 41 3 12 $21/2/83$ 13.0 7.2 20.0 15.0 0.30 2.6 2.5

42 1 5 $2/1/62$ 18.2 5.5 13.5 11.5 0.45 5.7

5.7 0.45 .5.7 \rm{V} 9.02 1.81 4.55 $\overline{0}$. 4.06 2.3 2.5 2.5 5.7 4.9 6.6 5.5 2.3 8.3 2.6 $\overline{1}$ 1.8 2.3 $(g \text{ cm}^{-3}) \text{ (m s}^{-1})$ 2.7 2.7 2.6 2.6 \triangleright Table 1. (*Cont.*) 7.0 density of alt. date of wire AS AS AS
(m) $(\text{dd}/\text{mm}/\text{yy})$ (mm) (kg m^{-1}) (cm) (g cm^{-3}) ⁻¹) (cm) $(g \text{ cm}^{-3})$

(30.0 18.0) (0.42)

(18.0 15.0) (0.42) 0.30 ${>}0.45$ AS 0.30 0.32 0.66 0.44 0.47 0.62 0.43 0.45 0.67 0.78 0.7 0.4 0.7 0.3 $\overline{7}$.0 11.5 15.0 size of AS >15 $\overline{10}$ 10 $\overline{15}$ $\frac{12}{11}$ \circ $\overline{11}$ ∞ 10.0 20.0 13.5 ∞ $\overline{19}$ no. ID (m) $(dd/\text{mm}/\text{y}y)$ (mm) (kg m⁻¹)
38 3 10 21/2/83 18.35 (11.8)
39 3 20 21/2/83 18.35 (8.9) 46 1 70 $27/2/72$ 18.2 5.6

47 1 40 $28/2/72$ 18.2 5

47 1 40 $28/2/72$ 18.2 5 49 1 60 $28/2/72$ 17.5 4.47
50 1 20 $7/4/76$ 22.4 6
50 1 20 $7/4/76$ 22.4 6 51 2 430 $16/1/72$ 25.3 4.9
 52 2 120 $5/2/75$ 18.2 5.7
 5.7 $\rm (kg~m^{-1})$ wt of 4.47 AS $\overline{1.1}$ 7.2 5.5 5.5 5.8 5.6 7.8 4.9 5.7 3.8 2.0 1.9 \overline{z} ъp \circ of wire diam. (mm) 18.35 18.35 13.0 13.0 18.2 18.2 13.0 18.2 18.2 22.4 18.2 17.5 25.3 18.2 9.6 22.4 9.6 0.5 $\frac{dd}{m}$ /yy) $21/2/83$ $25/2/63$ $16/3/70$ $27/2/72$ $28/2/72$ $28/2/72$ $16/1/72$ $21/2/83$ $21/2/83$ $1/2/70$ $28/2/72$ $7/4/76$ $5/2/75$ $16/2/68$ $15/2/68$ $12/3/69$ $21/2/83$ $2/1/62$ date $\binom{m}{m}$ \Box r. \circ 110 \mathfrak{a} \mathcal{C} \oplus 430 120 alt. Ω 12 \mathcal{L}_{1} 60 \mathbb{S} Ω \mathcal{S} $\overline{5}$ \triangle S ొ \sim ന $\overline{}$ \sim \sim ന ന \sim no. 39 42 $43\,$ 47 $\frac{8}{3}$ 49 $50\,$ 52 38 Θ $\overline{41}$ $\overline{4}$ $\frac{4}{5}$ $\frac{6}{5}$ $\overline{5}$ 53 \mathbb{Z} ည်

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Snowaccretiononoverhead wires ²⁹⁶³

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 ρ_S (observed)
Figure 12. Comparison between measured and calculated densities of accreted snow
(natural accretion) measured and calcula
(natural accretion).

(natural accretion).
In table 1 it is seen that some reported air temperatures are sub-freezing and In table 1 it is seen that some reported air temperatures are sub-freezing and indicates some of the errors included. However, such data have been used for the following analysis without any corrections In table 1 it is seen that some reported
indicates some of the errors included. Howe
following analysis without any corrections.
Using the same procedure as in the wind-ti dicates some of the errors included. However, such data have been used for the lowing analysis without any corrections.
Using the same procedure as in the wind-tunnel experiments, a multiple regression alysis gave the foll

following analysis without any corrections.
Using the same procedure as in the wind-tunnel experiments, a multiple regression
analysis gave the following empirical equation expressing density as a function of
hasic paramet Using the same p
analysis gave the f
basic parameters: %
 $\rho_{\rm SN} = 0.220\,69 + 0.294\,02V_{\rm N} - 0.200\,72_{\rm N}^{1.1} \; +$ $N^{1.1} + 0.09961.$ (3.13)

$$
\rho_{\rm SN} = 0.22069 + 0.29402V_{\rm N} - 0.20072_{\rm N}^{1.1} + 0.09961. \tag{3.13}
$$

 $\rho_{SN} = 0.22069 + 0.29402V_N - 0.20072_N^{1.1} + 0.09961.$ (3.13)
The number of data used for deriving the equation was $n = 34$ (selected from table 1,
taking reliability into account) and the multiple correlation coefficient w The number of data used for deriving the equation was $n = 34$ (selected from table 1, taking reliability into account), and the multiple correlation coefficient was $r = 0.942$.
In figure 12, the measured density is compar taking reliability into account), and the multiple correlation coefficient was $r = 0.942$.
In figure 12, the measured density is compared with the calculated value using (3.13). taking reliability into acce
In figure 12, the measured
In (3.13), the term $V^{1.1}$ is
avoiding density decrease 1.1 ig ount), and the multiple correlation coefficient was $r = 0.942$.
d density is compared with the calculated value using (3.13).
is included to avoid excessive densities over 1.0 and also for
es with increases in V_{N} In figure 12, the measured density is compared with the calculated value using (3.13).
In (3.13), the term $V^{1.1}$ is included to avoid excessive densities over 1.0 and also for
avoiding density decreases with increases

avoiding density decreases with increases in V_N .
The empirical equation derived from natural data predicts similar trends to wind-
tunnel experiments; that is, the density increases with wind speed and temperature. The empirical equation derived from natural data predicts similar trends to wind-
tunnel experiments; that is, the density increases with wind speed and temperature.
Moreover, a term dependent on precipitation intensity is tunnel experiments; that is, the density increases with wind speed and temperature.
Moreover, a term dependent on precipitation intensity is not included, since the range
of precipitation intensity included in observations Moreover, a term depender
of precipitation intensity in
not be clearly identified.
The author suspects tha of precipitation intensity included in observations was too narrow and its effect could not be clearly identified.
The author suspects that the density of snow just accreted will be lower than that

calculated using (3.13). Modifying (3.13) is an important task for future research.

Following the same procedure as in the wind-tunnel experiments, the empirical equation expressing the accretion efficiency as a function of basic parameters was

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 α (calculated from measurements)
Figure 13. Comparison between α measured and calculated by equation (3.14) (en α measured and can (natural accretion).

derived as follows:

rs:
\n
$$
\alpha_{\rm N} = \exp\{-1.01 + 4.37T_{\rm R} - 6.89T_{\rm R}^2 - 0.0169P_nt\}.
$$
\n(3.14)

 $\alpha_{\rm N} = \exp\{-1.01 + 4.37T_{\rm R} - 6.89T_{\rm R}^2 - 0.0169P_nt\}.$ (3.14)
Here, the number of data points used was $n = 24$, with the multiple correlation coef-
ficient $r = 0.938$ In figure 13 calculated accretion efficiencies based Example 13. Here, the number of data points used was $n = 24$, with the multiple correlation coef-
ficient $r = 0.938$. In figure 13, calculated accretion efficiencies based on observations
given in table 1 are compared wit ficient $r = 0.938$. In figure 13, calculated accretion efficiencies based on observations given in table 1 are compared with those calculated from (3.14). Equation (3.14) ficient $r = 0.938$. In figure 13, calculated accretion efficiencies based on observations
given in table 1 are compared with those calculated from (3.14). Equation (3.14)
is applicable for $P_n t$ less than 40. Beyond this given in table 1 are compared with those calculated from (3.14). Equation (3.14) is applicable for $P_n t$ less than 40. Beyond this limit, the calculated mass of snow decreases with increasing values of $P_n t$. This is clea ations. decreases with increasing values of $P_n t$. This is clearly in contradiction of real situations.
On inspection of (3.9), it is clear that if the higher density of accreted snow is

ations.
On inspection of (3.9), it is clear that if the higher density of accreted snow is
used then, keeping all other parameters the same, a higher accretion efficiency is
predicted predicted. In conclusion, equation (3.14) may predict accretion efficiency higher than in real unations.

situations.

(*e*) *Investigations to modify the empirical model*

Because of the above conclusion, efforts in modifying the model in order to give estimates for more reliable density and accretion efficiency have been continued.
In parallel with collecting more reliable data on patural accretion, a worldwide Because of the above conclusion, efforts in modifying the model in order to give
timates for more reliable density and accretion efficiency have been continued.
In parallel with collecting more reliable data on natural acc

estimates for more reliable density and accretion efficiency have been continued.
In parallel with collecting more reliable data on natural accretion, a worldwide
survey of models proposed by other researchers and engineer In parallel with collecting more reliable data on natural accretion, a worldwide
survey of models proposed by other researchers and engineers has been made (see
also the suggestions given in papers presented at IWAIS, rev survey of models proposed by other researchers and engineers has been made (see
also the suggestions given in papers presented at IWAIS, reviewed and summarized
in Admirat *et al.* (1990) and Sakamoto & Miura (1993)). Amon also the suggestions given in papers presented at IWAIS, reviewed and summarized
in Admirat *et al.* (1990) and Sakamoto & Miura (1993)). Amongst these, Admirat *et
al.* (1988*b*) proposed models estimating density based o al. (1988b) proposed models estimating density based on observations in France for *Phil. Trans. R. Soc. Lond.* A (2000)

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2966 $Y. Sakamoto$
relatively low wind speed and also proposed that the accretion efficiency is inversely relatively low wind speed and also proposed that the accretion efficiency is inversely
proportional to the wind speed. Use of their simple form of accretion efficiency has
considerable advantages (see also Makkonen & Ahti relatively low wind speed and also proposed that the accretion efficiency is inversely
proportional to the wind speed. Use of their simple form of accretion efficiency has
considerable advantages (see also Makkonen & Ahti proportional to the wind speed. Use of their simple form of accretion efficiency has
considerable advantages (see also Makkonen & Ahti 1993). On the other hand, Fin-
stead *et al.* (1988) proposed a model in which the accr considerable advantages (see also Makkonen & Ahti 1993). On the other hand, Finstead *et al.* (1988) proposed a model in which the accretion efficiency was inversely proportional to the product of wind speed and diameter stead *et al.* (1988) propose
proportional to the product
action of wind as follows: $\alpha = 0.038T_A/(V_N D).$ (3.15)

$$
\alpha = 0.038T_A/(V_{\rm N}D). \tag{3.15}
$$

 $\alpha = 0.038T_A/(V_N D).$ (3.15)
In this model, it is also assumed that the accretion efficiency is proportional to the
air temperature. This tendency is qualitatively consistent with the author's model In this model, it is also assumed that the accretion efficiency is proportional to the air temperature. This tendency is qualitatively consistent with the author's model at lower ranges in temperature but is, however, cle In this model, it is also assumed that the accretion efficiency is proportional to the air temperature. This tendency is qualitatively consistent with the author's model at lower ranges in temperature but is, however, clea air temperature. This tendency is qualitatively consistent with the author's model
at lower ranges in temperature but is, however, clearly in contradiction at higher
temperature. Thus the Ervik model has obvious limitation at lower ranges in temperature but is, however, clearly in contradiction at higher

temperature. Thus the Ervik model has obvious limitations.
The author has attempted to combine his empirical model with that of Ervik.
Employing (3.15) in the standard cylindrical snow-sleeve model (see (3.3)), yields
the The author 1
Employing (3.1
the following:

$$
2\pi R \rho_{\rm S} dR = -\frac{38T_{\rm A}}{V_{\rm N}} P_n dt.
$$
\n(3.16)

 $2\pi R \rho_{\rm S} dR = -\frac{R}{V_{\rm N}} P_n dt.$ (3.16)
In this equation, it is pointed out that the 2R in the right-hand side of (3.3) was
eliminated as it was assumed that accretion efficiency is inversely proportional to the In this equation, it is pointed out that the $2R$ in the right-hand side of (3.3) was
eliminated as it was assumed that accretion efficiency is inversely proportional to the
diameter of accreted snow Integrating (3.16) yi In this equation, it is pointed out that the $2R$ in the eliminated as it was assumed that accretion efficiency is diameter of accreted snow. Integrating (3.16) yields

ntegrating (3.16) yields
\n
$$
\pi \rho_{\rm S}(R^2 - R_0^2) = \frac{38T_{\rm A}}{V_{\rm N}} P_n t.
$$
\n(3.17)

 $\pi \rho_S (R^2 - R_0^2) = \frac{S - R}{V_N} P_n t.$
Since the mass of accreted snow per unit length of wire is

$$
W = \pi \rho_{\rm S}(R^2 - R_0^2),
$$
 (3.18)

there results a simple equation for the mass of accreted snow, namely

$$
W = \frac{38T_{\rm A}}{V_{\rm N}} P_n t. \tag{3.19}
$$

 $W = \frac{3.19}{V_N} P_n t.$ (3.19)
For cases in which the wind speed is high, P_n is approximately equal to the pre-
intation rate water equivalent multiplied by the wind speed. This implies that the For cases in which the wind speed is high, P_n is approximately equal to the precipitation rate water equivalent multiplied by the wind speed. This implies that the mass of accreted snow is then approximately equal to th For cases in which the wind speed is high, P_n is approximately equal to the precipitation rate water equivalent multiplied by the wind speed. This implies that the mass of accreted snow is then approximately equal to th cipitation rate water equivalent multiplied by the wind speed. This implies that the
mass of accreted snow is then approximately equal to the precipitation rate multi-
plied by the air temperature during accretion. Here it mass of accreted snow is then approximately equal to the precipitation rate multi-
plied by the air temperature during accretion. Here it is especially noted that the
density does not appear in the equation for calculatin plied by the air temperature during accretion. Here it is especially noted that the density does not appear in the equation for calculating the mass of accreted snow.
This is because, in (3.17), an increment of sectional density does not appear in the equation for calculating the mass of accreted snow.
This is because, in (3.17), an increment of sectional area of accreted snow $\pi(R^2 - R_0^2)$ is inversely proportional to the amount of snow This is because, in (3.17), an increment of sectional area of accreted snow $\pi(R^2 - R_0^2)$ is inversely proportional to the amount of snow contributing to accretion (the right-hand side of (3.17)) and it was assumed that is inversely proportional to the amount of snow contributing to accretion (the right-
hand side of (3.17)) and it was assumed that this increment in mass was independent
of the diameter of the accreted snow.
The above e hand side of (3.17) and it was assumed that this increment in mass was independent

of the diameter of the accreted snow.
The above equation is very simple and convenient for practical applications. On
calibrating the equation for the data given in table 1, it was found not to be applicable
for wet-snow i The above equation is very simple and convenient for practical applications. On calibrating the equation for the data given in table 1, it was found not to be applicable for wet-snow incidents in Japan. As mentioned previo calibrating the equation for the data given in table 1, it was found not to be applicable
for wet-snow incidents in Japan. As mentioned previously, there is an air tempera-
ture at which the accretion efficiency is a maxim for wet-snow incidents in Japan. As mentioned previously, there is an air tempera-
ture at which the accretion efficiency is a maximum. Therefore, combining the idea
of Ervik that the accretion efficiency is inversely prop ture at which the accretion efficiency is a maximum. Therefore, combining the idea
of Ervik that the accretion efficiency is inversely proportional to the diameter of
accreted bodies, and incorporating the fact that accret of Ervik that the accretion efficiency is inversely proportional to the diameter of accreted bodies, and incorporating the fact that accretion efficiency attains a maximum at some temperature, the following equation is pro

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accretion efficiency:

$$
\alpha = a \frac{\exp\{b(T/T_D - c)^2\}}{V_N^G D},
$$
\n(3.20)

 $\alpha = a \longrightarrow V_N^G D$ (3.20)
where a, b, c and G are unknown constants. Attempts were made to find values of
these constants by best-fitting data by trial and error and this vielded the following where a, b, c and G are unknown constants. Attempts were made to find values of these constants by best-fitting data by trial and error and this yielded the following equation for determining the mass of accreted snow p where a , b , c and G are unknown constants. Attempts were made to find values these constants by best-fitting data by trial and error and this yielded the foll equation for determining the mass of accreted snow per

ng the mass of accreted snow per unit length of wire:
\n
$$
W = 4.5 \frac{\exp\{-6(T/T_D - 0.32)^2\}}{V_N^{0.2}} P_n t.
$$
\n(3.21)

 $W = 4.5$ $\frac{V_{\text{N}}^{0.2}}{V_{\text{N}}^{0.2}}$ $P_n t$. (3.21)
While this equation includes uncertainty included in the data of table 1, for the
present it is recommended to estimate snow load design of projected power lines in While this equation includes uncertainty included in the data of table 1, for the present it is recommended to estimate snow load design of projected power lines in conjunction with $(3\ 12)$ and $(3\ 13)$ While this equation includes uncert
present it is recommended to estimate
conjunction with (3.12) and (3.13) . % conjunction with (3.12) and (3.13) .
4. Statistical distribution used for establishing design snow load

4. Statistical distribution used for establishing design snow load
In establishing the design snow load for any power line, it is necessary to select
an appropriate statistical distribution. In the Technical Report 826 (IE In establishing the design snow load for any power line, it is necessary to select
an appropriate statistical distribution. In the Technical Report 826 (IEC 1991), it
is recommended that a type-I extreme value distribution In establishing the design snow load for any power line, it is necessary to select
an appropriate statistical distribution. In the Technical Report 826 (IEC 1991), it
is recommended that a type-I extreme value distribution an appropriate statistical distribution. In the Technical Report 826 (IEC 1991), it
is recommended that a type-I extreme value distribution (Gumbel distribution) is
applied for the snow load, but this may present problems is recommended that a type-I extreme value distribution (Gumbel distribution) is
applied for the snow load, but this may present problems in some regions. Pezard
(1993) pointed out that there are regions where snow accreti applied for the snow load, but this may present problems in some regions. Pezard (1993) pointed out that there are regions where snow accretion is not normally experienced but which may have extremely high snow load with v (1993) pointed out that there are regions where snow accretion is not normally experienced but which may have extremely high snow load with very low probability; Pezard suggests that in these rare cases a Poisson-type distribution would be more appropriate for expressing real situations. This suggestion implies the possibility that severe damage to lines may be encountered for cert appropriate for expressing real situations. This suggestion implies the possibility that severe damage to lines may be encountered for certain regions where normally no
line damages due to snow have been experienced. In fact, for some areas in Japan,
it has been found that, when estimating snow load based on c line damages due to snow have been experienced. In fact, for some areas in Japan,
it has been found that, when estimating snow load based on climatological records,
data samples may indicate larger values of sample standar it has been found that, when estimating snow load based on climatological records,
data samples may indicate larger values of sample standard deviations than the mean
values and this throws doubt on the application of the data samples may indicate larger values of sample standard deviations than the mean
values and this throws doubt on the application of the type-I distribution. Occurrence
of heavy wet-snow load is a phenomenon which happen values and this throws doubt on the application of the type-I distribution. Occurrence
of heavy wet-snow load is a phenomenon which happens only when several conditions
are satisfied, such as a high intensity of precipitat of heavy wet-snow load is a phenomenon which happens only when several conditions
are satisfied, such as a high intensity of precipitation, an air temperature suitable
for accretion, suitable wind speed and direction, toge are satisfied, such as a high intensity of precipitation, an air temperature suitable
for accretion, suitable wind speed and direction, together with sufficient time for
accretion. Note that such conditions do not promote for accretion, suitable wind speed and direction, together with sufficient time for accretion. Note that such conditions do not promote the shedding of snow from wire. If the occurrence probability of such snow events is l accretion. Note that such conditions do not promote the shedding of snow from
wire. If the occurrence probability of such snow events is low enough the application
of a type-I extreme value distribution may not be acceptab wire. If the occurrence probability of such snow events is low enough the application
of a type-I extreme value distribution may not be acceptable and the author is
in agreement with Pezard's suggestion. Consequently, atte of a type-I extreme value distribution may not be acceptable and the author is
in agreement with Pezard's suggestion. Consequently, attempts are made to find
limitations for the application of certain types of distribution in agreement with Pezard's suggestion. Consequently, attempts are made to find
limitations for the application of certain types of distribution, taking into account
the occurrence frequency of each event leading to the sev

5. Concluding remarks

5. Concluding remarks
This paper deals first with the fundamentals of snow accretion on overhead wires,
namely the meteorological conditions. There follows a discussion of the suspected This paper deals first with the fundamentals of snow accretion on overhead wires,
namely the meteorological conditions. There follows a discussion of the suspected
mechanisms whereby a snow sleeve can form around wires inc This paper deals first with the fundamentals of snow accretion on overhead wires, namely the meteorological conditions. There follows a discussion of the suspected mechanisms whereby a snow sleeve can form around wires, in heat balance on the surface of the wire, to deduce the thermodynamic state of the suspected mechanisms whereby a snow sleeve can form around wires, including the use of heat balance on the surface of the wire, to deduce th mechanisms whereby a snow sleeve can form around wires, including the use of heat balance on the surface of the wire, to deduce the thermodynamic state of the accreted snow. Finally, an account is given of progress directe accreted snow. Finally, an account is given of progress directed towards estimating.

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**MATHEMATICAL,
PHYSICAL
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PHILOSOPHICAL
TRANSACTIONS

 $Y.$ Sakamoto
The reason why these aspects have been selected is because there is less consensus The reason why these aspects have been selected is because there is less consensus
in our understanding of snow accretion than of ice accretion (glaze and rime ice). So
as to avoid repeating research and to accelerate furt The reason why these aspects have been selected is because there is less consensus
in our understanding of snow accretion than of ice accretion (glaze and rime ice). So
as to avoid repeating research and to accelerate furt as to avoid repeating research and to accelerate further progress it is thought that a summary of past experiences would prove useful. to avoid repeating research and to accelerate further progress it is thought that a
mmary of past experiences would prove useful.
As previously described, severe damage to power lines has been experienced due to
avv overlo

summary of past experiences would prove useful.
As previously described, severe damage to power lines has been experienced due to
heavy overload caused by wet-snow accretion superposed with wind load. In addition,
shedding As previously described, severe damage to power lines has been experienced due to heavy overload caused by wet-snow accretion superposed with wind load. In addition, shedding of accreted snow promotes unbalanced tension in heavy overload caused by
shedding of accreted snot
damage to power lines.
Fortunately through i edding of accreted snow promotes unbalanced tension in wires, leading to further
mage to power lines.
Fortunately, through meetings such as IWAIS, IEC and the CIGRE task force
riging (see IEC 1997), opportunities for the e

damage to power lines.
Fortunately, through meetings such as IWAIS, IEC and the CIGRE task force
for icing (see IEC 1997), opportunities for the exchange of recent information has Fortunately, through meetings such as IWAIS, IEC and the CIGRE task force
for icing (see IEC 1997), opportunities for the exchange of recent information has
increased significantly. It is expected that research work on wet for icing (see IEC 1997), opportunities for
increased significantly. It is expected that
will progress rapidly in the near future.
The problems that remain are listed as creased significantly. It is expected that research v
Il progress rapidly in the near future.
The problems that remain are listed as follows.

- (a) a method for estimating the density of accreted snow on wires more accurately
(b) A method for estimating the density of accreted snow on wires more accurately based on meteorological parameters.
	- (b) A method for estimating the accretion efficiency more accurately based on meteorological parameters.
	- (c) The effect of torsional rigidity of a wire span on the mass of accreted snow.
	- (c) The effect of torsional rigidity of a wire span on the mass of accreted snow.

	(d) Conditions under which snow shedding occurs (the effect of the current carried

	by the wire solar radiation temperature wind etc.) Conditions under which snow shedding occurs (the effect by the wire, solar radiation, temperature, wind, etc.).
	- by the wire, solar radiation, temperature, wind, etc.).
(e) Statistical distributions applicable to certain regions.
	- (e) Statistical distributions applicable to certain regions.

	(f) The type of snow shedding (shed simultaneously over the entire span or shed

	partly) and conditions under which snow sheds. Such phenomena affect the The type of snow shedding (shed simultaneously over the entire span or shed
partly) and conditions under which snow sheds. Such phenomena affect the
torsional and bending loads on supporting structures due to unequal tensi The type of snow shedding (shed simultaneously over the entire span or shed partly) and conditions under which snow sheds. Such phenomena affect the torsional and bending loads on supporting structures due to unequal tensi partly) and conditions under which snow sheds. Such phenomena affect the torsional and bending loads on supporting structures due to unequal tension in wires.
	- (g) Change in characteristics of snow after accretion (freezing due to the decrease
of temperature increase in density and mass due to light rain etc.) change in characteristics of snow after accretion (freezing due to the cof temperature, increase in density and mass due to light rain, etc.).
	- (s) of temperature, increase in density and mass due to light rain, etc.).

	(h) Methods for treating incidents of wet-snow accretion combined with other types of icing in a single icing event. of compensative, merceive in dense
Methods for treating incidents of
of icing in a single icing event.

of icing in a single icing event.
The author is deeply indebted to a number of experts worldwide who have had discussions with
him and exchanged invaluable ideas and suggestions regarding icing problems: in particular The author is deeply indebted to a number of experts worldwide who have had discussions with
him and exchanged invaluable ideas and suggestions regarding icing problems; in particular,
those delegates of UWAIS and related The author is deeply indebted to a number of experts worldwide who have had discussions with
him and exchanged invaluable ideas and suggestions regarding icing problems; in particular,
those delegates of IWAIS and related him and exchanged invaluable ideas and suggestions regarding icing problems; in particular,
those delegates of IWAIS and related meetings. Also my thanks go to the staff of Electricité
de France, CRIEPI and the utilities o de France, CRIEPI and the utilities of Japan that have participated in the wet-snow research project.

I greatly appreciate this opportunity to review the present state of wet snow research.

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I greatly appreciate this opportunity to review the present state of wet snow research.
My special thanks go to Professor Poots, who spent a long time modifying my original paper
d Miss B. Kajiwara of MoBIT, for her I greatly appreciate this opportunity to review the present state of wet
My special thanks go to Professor Poots, who spent a long time modifyi
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