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Final Report

EVALUATION OF AN ICING-INDICATOR PROBE

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ABSTRACT

The performance of an icing indicator proposed by Tribus and Moyle was evaluated theoretically and experimentally. The indicator consists of two conducting elements in a nonconducting aerofoil, with the forward element exposed to the impingement of airborne particles and the rear element sheltered. The analysis shows that a probe can be designed to be insensitive to airstream velocity and changes in the ambient temperature. Ice clouds and water clouds above the freezing point will not produce a response which can be misinterpreted as icing conditions. The instrument will give an indication of the icing rate with a moderate ice cap but the performance will deteriorate.

In general the performance tests confirmed the theoretical analysis. The minimum icing rate which could be detected and the sensitivity of the device to design details were determined.

EVALUATION OF AN ICING INDICATOR PROBE

INTRODUCTION

Continuous indication of the existence and intensity of icing conditions about aircraft is desirable from an operational and safety point of view. The pilot may take appropriate action upon such indication, or the indicator may actuate the ice-protection equipment of the aircraft.

The work reported here was undertaken to evaluate an icing indicator conceived by Myron Tribus and Morton Moyle while working on Air Force research contract AF18(600)-51. The indicator is essentially an improvement on one developed by W. Findeisen in Germany.

FINDEISEN'S DETECTION METHOD

Findeisen suggested an icing detector based on the energy released at a surface by the formation of ice.[1] In general terms, Findeisen's device has two surfaces exposed to the air stream in which the plane is flying. One of these surfaces is placed so that airborne particles impinge on it; the other is sheltered from such particles. In nonicing conditions both surfaces assume the temperature of the airstream. In icing conditions the temperature of the exposed surface is raised due to ice formation, while the sheltered surface is unaffected. The temperature rise of the exposed surface above that of the sheltered surface is thus an indication of icing. The temperature difference can be measured by any convenient method. This scheme has the important advantage of distinguishing icing conditions from nonicing water and from ice clouds. Water above the freezing point and solid ice particles either have no effect or cool the exposed surface.

Certain conditions other than icing can raise the temperature of the exposed surface of Findeisen's device above that of the sheltered one. One of these conditions occurs when the aircraft flies through regions of variable air temperature; if one of the two surfaces approaches the new ambient temperature more rapidly than the other, there will be a transient period during which the two surfaces are at different temperatures and the instrument may give a spurious indication of icing when there is none. Only if the transient thermal response of the two elements is the same will spurious icing signals be avoided for all changes of ambient temperature. Frictional heating of a surface in a high-velocity airstream can also give a spurious icing signal. The frictional heating is different at different parts of a body, and in Findeisen's icing indicator the exposed element was heated more than the sheltered one, so that spurious readings were produced by high-speed flight.

Findeisen made an attempt to eliminate the spurious signals by painting part of his instrument with a lacquer; but control of the thickness of the lacquer coating is difficult, and excessive experimentation would be required to determine if the spurious signals will be eliminated for all flight velocities.

INDICATOR PROPOSED BY TRIBUS AND MOYLE

In 1952, Tribus and Moyle proposed an ice-warning probe which also is based on the energy release on a surface where ice is forming, but which is designed to eliminate spurious icing signals from frictional heating or variable air-stream temperature.

The probe has two conducting elements inserted in a nonconducting aerofoil as shown in Fig. 1. The front element is exposed to the impingement of airborne particles, but the rear element is sheltered because the aerofoil becomes narrower toward the tail. As with Findeisen's instrument, the temperature of the front element becomes higher than the rear in icing conditions, and this temperature difference is detected by some convenient means. The equations governing convective heat transfer can be used to explain how the probe avoids spurious signals from frictional heating and from changing ambient temperatures.

The rate of convective heat transfer between a body and an air-stream becomes zero, not when the body is at the same temperature as the air stream, but when the body is at a higher temperature called the adiabatic wall temperature. The difference between the air temperature and the adiabatic wall temperature is not significant for low velocities, but may be appreciable at the velocities attained by modern aircraft. Data for the local rate of heat exchange expressed as energy transferred per unit time per unit area are generally correlated in terms of a heat transfer coefficient, i.e.,

$$\text{heat transfer rate} = \frac{dq}{dA} = h(t_a - t_s) \qquad (1)$$

where: h = ordinary heat transfer coefficient

t_a = adiabatic wall temperature

t_s = temperature of surface

dA = differential element of area.

The rate on the right must be integrated over the whole surface to give the total rate of heat transfer. The rate of change in the temperature of the body will in turn be proportional to the rate of heat transfer:

$$C\frac{dt_s}{dA} = \int h(t_a - t_s)dA \qquad (2)$$

where: C = thermal capacity of body (dimensions: energy/o)

θ = time.

The adiabatic wall temperature can be expressed as

$$t_a = t_o + r(t_t - t_o) \qquad (3)$$

where: t_o = temperature of the air stream

t_t = the total temperature

and r = the recovery factor.

Introducing Equation 3 into Equation 2 gives

$$(t_o - t_s) + \bar{r}(t_t - t_o) = \frac{C}{A\bar{h}}\frac{dt_s}{d\theta} \qquad (4)$$

where the symbols with bars are average values defined by

$$\bar{r} = \frac{\int hr\ dA}{\int h\ dA} \tag{5}$$

$$\bar{h} = \frac{\int h\ dA}{A} . \tag{6}$$

Equation 4 can be integrated to give

$$(t_o - t_s) + \bar{r}\ (t_t - t_s) = K \exp\left(- \frac{\bar{h}A}{C} \theta\right) . \tag{7}$$

K is a constant equal to the value of the left side of the equation for θ equal to zero. Solving explicitly for the surface temperature gives

$$t_s = t_o + \bar{r}(t_t - t_o) - K \exp\left(- \frac{\bar{h}A}{C} \theta\right) . \tag{8}$$

For two bodies in the same airstream (such as the front and rear elements of the Tribus-Moyle icing indicator), t_o and t_t will be the same. It is then evident from Equation 8 that $\bar{r}$ must be the same for the two bodies if they are to have the same surface temperatures at equilibrium. If in addition the two bodies are to have the same temperature during the transient period when the exponential term is significant, the coefficient of θ in the exponential term must be the same for both bodies. The proper design of an icing indicator, in order to avoid spurious signals from frictional heating or ambient temperature changes, thus requires that the values of $\bar{r}$ be the same for the front and rear elements, and also that $(\bar{h}A/C)$ be the same for the front and rear elements.

In the Tribus-Moyle indicator, the rear element is placed in the region of turbulent flow where the recovery factor is equal to the third root of the Prandtl modulus.[2] The recovery factor may then be taken as 0.9 for the rear element. The front element is placed in the cylindrical leading edge of the indicator probe. In the laminar flow which occurs near the stagnation point of a cylinder, both the heat transfer coefficient h and the recovery factor r are functions of angular deviation from the stagnation point. In particular, the recovery factor is higher than 0.9 at the stagnation point and lower than this value farther back, and it is possible to choose the size of the front element so that it will have an average recovery factor $\bar{r}$ equal to that of the rear element. The process is as follows: The local heat transfer coefficient for a cylinder can be evaluated from an expression such as that of Schmidt and Wenner:[3]

$$\frac{hD}{k} = 1.14\, P_r^{0.4} \left(\frac{v}{\nu}\right)^{0.5} \left[1 - \left(\frac{\phi}{1.57}\right)^3\right] \qquad (9)$$

where: D = diameter of cylinder

k = thermal conductivity of gas

P_r = Prandtl modulus = 0.73 for air

v = velocity of gas stream

ν = kinematic viscosity

ϕ = angle from stagnation point (in radians)

Local values of the recovery factor given by Eckert and Weise[4] are reproduced in Table I.

TABLE I

ϕ (degrees)	$\bar{r}$
0	1.00
15	.98
30	.90
45	.79
65	.70

When Equation 9 is introduced into Equation 5, the expression becomes

$$\bar{r} = \frac{\int r\left[1 - \left(\frac{\phi}{1.57}\right)^3\right]d\phi}{\int \left[1 - \left(\frac{\phi}{1.57}\right)^3\right]d\phi} . \qquad (10)$$

The integrands that appear in Equation 10 are plotted in Fig. 2. It is necessary to choose an upper limit for the integration so that $\bar{r}$ will be equal to 0.9. The correct value for the upper limit is about 55°, i.e., the front element will have the same equilibrium temperature as the rear element if it extends to a position 55° back from the stagnation point of the cylinder.

The transient response of the front and rear elements can then be made equal by adjusting the heat capacity of the two elements so that

$$(\bar{h}A/C)_{\text{front}} = (\bar{h}A/C)_{\text{rear}} \qquad (11)$$

The ratio of the thermal capacities of the two elements can be evaluated with the aid of Equation 9 which is applicable to the front element and an equation given by Jacob and Dow[5] which is applicable to the rear element:

$$\frac{\bar{h}L}{k} = 0.0280\left(\frac{VL}{\nu}\right)^{0.8}\left[1 + 0.40\left(\frac{L'}{L}\right)^{2.75}\right] \qquad (12)$$

where: L' = distance from stagnation point to beginning of element

L = distance from stagnation point to end of element.

The ratio of the heat capacities then becomes

$$\frac{C_{rear}}{C_{front}} = 0.028\,\frac{A_{rear}}{Ll}\left(\frac{L}{D}\right)^{0.8}\left(\frac{VD}{\nu}\right)^{0.3}\frac{1 + 0.40\left(\frac{L'}{L}\right)^{2.75}}{\left[1 - \left(\frac{\phi}{1.57}\right)^{3}\right]d\phi} \qquad (13)$$

where: l = length of front element along axis of cylinder.

An examination of Equation 13 shows that the time constants of the two elements cannot be equalized, irrespective of the Reynolds modulus. However, the Reynolds modulus appears only to the 0.3 power in the expression so that the ratio of thermal capacities is not very sensitive to the velocity. In fact, when the velocity changes by a factor of 2, the correct ratio for the thermal capacities will change only 23 per cent. By designing for the center of the velocity range of the aircraft, the time constants can be pretty well matched for all velocities. It does appear, however, that it would be desirable to use different thermal capacities for aircraft whose flying speeds differ considerably from each other.

THEORETICAL PERFORMANCE OF INDICATOR

It will now be worthwhile to review the performance which theoretical considerations indicate for an icing detector as suggested by Tribus and Moyle. In clear air the two elements will have the same equilibrium temperature no matter what the ambient temperature of flight velocity. If the aircraft encounters an air mass with a different temperature than that in which it has been flying, the two elements will continue to have equal temperatures if the aircraft is flying at the "design speed" (i.e., the speed used in Equation 13). If the speed is less than the "design speed", the front element will respond to the new ambient temperature more rapidly than the rear element; if the speed is greater than the "design speed", the front element will approach the new ambient less rapidly than the rear element. A spurious signal similar to that induced by icing conditions will occur when entering colder air at speeds higher than the design speed, and when entering warmer air at speeds lower than the design speed. In any case the temperature difference will be small unless the flight speed differs greatly from the design speed. For example, if an aircraft suddenly enters an air mass with a different temperature while flying at a speed 10 per cent above the design speed, the maximum temperature difference between the elements will be about 1 per cent of the difference in temperature between the two air masses.

When the detector flies through water clouds above the freezing point, water will collect on the front element where some of it will evaporate, cooling the element. Water may or may not run back to the rear element depending on how fast drops collect on the front surface of the indicator. If water does run to the rear element, it will also be cooled and the two elements will have the same temperature; in any case, the front element will not be warmer than the rear.

In cold ice clouds the ice particles will bounce off the front element and produce no effect different from that which would occur in clear air. If the air cloud is only a little below freezing, frictional heating may raise the temperature of the elements above freezing so that the ice particles melt when they hit the front element and thus cool it. Again no situation arises in which the front element becomes warmer.

When the instrument encounters icing conditions, the ice forming on the front element liberates heat. The temperature of the front element, therefore, rises until a steady-state condition is produced when the heat liberated by the heat of fusion of the ice is carried away from the element by convection and by sublimation. The steady-state condition has been analyzed by Messinger[6], and the temperatures of the front and rear elements can be calculated by the methods which he presents. However, as a rough approximation, the heat supplied is proportional to the rate of ice formation, and the heat carried away is proportional to $\bar{h}(t_s - t_a)$. Since the rear element assumes the adiabatic wall temperature, the temperature difference between the elements will be an approximate measure of the icing rate, provided $\bar{h}$ remains constant. However, $\bar{h}$ depends on the velocity of the airplane and no universal calibration of the instrument can be achieved. In any one icing encounter the readings of the instrument should be an indication of the relative intensity of icing from instant to instant.

A qualitative picture may be obtained of the performance of the indicator as an ice accretion builds up on the front element. Heat exchange between the front element and the exposed surface will have to take place through a layer of ice and the temperature of the element will therefore respond less quickly to changing conditions at the surface. Also the ice cap will add its heat capacity to that of the front element and will alter the effective angular extent of the front element, so that the balance of recovery factors and time constants between the two elements will gradually be distorted. However, the basic detection principle will continue to operate with the front surface of the ice layer rising in temperature by an amount that is about proportional to the icing rate. In short, the instrument continues to operate, but in a way equivalent to a poorly designed instrument.

LABORATORY PERFORMANCE TESTS

In order to check the foregoing theoretical analysis, to examine questions which theory cannot answer, and to obtain practical experience in the operation of the icing indicator, an experimental program was undertaken. The program can be considered in two parts. The first part of the experimental program was conducted at low velocities (about 100 ft/sec) with the indicator exposed to various conditions of rain and icing clouds. The second part was conducted at higher velocities (up to about 800 ft/sec) and was designed primarily to check the calculations for the angle of the front element and for the ratio of the thermal capacities of the two elements.

Several indicator probes were constructed of aluminum and plastic as shown in Fig. 3. Thermistors* were inserted in the front and rear elements and connected in a bridge circuit as shown in Fig. 4. This circuit was suggested by Findeisen and is a rather obvious way to make the instrument sensitive only to differences in temperature between the two elements. A vacuum-tube voltmeter was usually used as the detector.

The first part of the experimental program was conducted in a small wind tunnel situated in a refrigerated room. The tunnel had a fixed

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*Some were supplied by Western Electric Company and others by Victory Engineering Corporation.

air velocity of about 100 ft/sec and was driven by an exhaust fan downstream from the test section. Water could be sprayed into the tunnel entrance to simulate cloud conditions. A DeVilbis air-atomizing nozzle was used to produce a spray similar to that found in natural clouds. The equipment was not suitable, however, for measurement of the water content of the air stream. One series of tests in this tunnel showed that the front element became cooler than the rear when the instrument was exposed to water clouds at temperatures above freezing. This result confirms the expectation that water clouds above the freezing point will not produce an indication that can be confused with icing.

Another series of tests was run with the air temperature below freezing. The results are shown in Fig. 5 where the output of the detector is plotted against the ambient temperature. With the ambient temperature only slightly below freezing and a high water content, the rate of ice formation is controlled by the maximum rate at which heat can be transferred from the surface. The icing rate, therefore, can be expected to increase linearly as the ambient temperature falls below the ice point. The theoretical maximum output will occur if the rear element remains at the ambient temperature and the front rises to 32°F. The maximum output can be calculated from the constants of the bridge circuit and the temperature coefficient of the thermistors. It can be seen that in most cases the indicator realizes the theoretical value. The one point above the curve is probably an erroneous reading. A few points lie significantly below the theoretical curve. It is not certain what caused these deviations, but water may have impinged so fast on the front surface that some of it ran back as far as the rear element before it completely froze. This would then heat the rear element and reduce the temperature difference between the elements.

A number of the points plotted in Fig. 5 were obtained with an ice cap on the instrument. The ice did not affect the magnitude of the detector readings but noticeably influenced the response time of the instrument. With a clean probe the detector voltage rose to its full value in less than a second; with about 0.1 inch of ice on the probe about 4 or 5 seconds were required to obtain the full value. It appeared that the instrument would work tolerably well with up to 0.1 inch of ice cap.

The second part of the experimental program was conducted in one of the University of Michigan's supersonic wind tunnels. A sonic throat was produced downstream of the test section by partially closing a valve so that subsonic velocities were produced in the test section. The velocity in the test section could be controlled by the valve, but since the total temperature of the airstream could not be controlled, a particular ambient temperature was associated with each velocity and could not be controlled independently from the velocity. The coupling of ambient temperature and velocity was not a serious shortcoming since the probe was designed to have no response to either velocity or temperature changes, and this series of tests was intended to see if the design has been successful.

The general procedure in these tests was to mount the indicator probe in the test section, start the tunnel, and then change the velocity and temperature of the airstream. Throughout the test the output of the indicator was observed or recorded. In a final series of runs, the probe was connected to equipment constructed by The Detroit Controls Corporation which permitted the output of the probe to be expressed directly in terms of temperature. The results of these runs are summarized in Table II.

TABLE II

TESTS IN HIGH-SPEED TUNNEL

Run	Tunnel Conditions	Output at Equilibrium*	Comments
13 Probe X	Initially 44°F, 130 knots		
	Changed to 13°F, 379 knots	+3.0°F	
	Changed to 44°F, 130 knots	-1.5	
14 Probe X	Initially 44°F, 130 knots		
	Changed to 17°F, 362 knots	+2.0	
	Changed to 42°F, 159 knots	-0.3	
15 Probe Y	Initially 44°F, 130 knots		
	Changed to 12°F, 385 knots	0.0	Front element went 2.0°F cold during transient.
	Changed to 43°F, 145 knots	+1.0	Front went 1.0°F warm during transient.
16 Probe Y	Initially 43°F, 144 knots		
	Changed to 1°F, 506 knots	+0.3	Front went 2.0°F cold during transient.
	Changed to 44°F, 112 knots	+0.3	Front went 2.0°F warm during transient.

*The output is the change in the temperature of the front element relative to the rear which occurred with the change in tunnel conditions. For example, in Run 13, when the temperature was dropped the quantity ($t_{front}-t_{rear}$) increased 3°F. When the temperature was raised again the quantity decreased 1.5°F.

Probe X, used in the first two runs was one of standard design. Probe Y was built with a smaller angle on the front element (45°) and with a smaller mass in the front element (0.7) than the standard. The test of Probe Y served to indicate how important small deviations from the design would be. It is concluded from these tests that spurious responses from the instrument have a magnitude corrsponding to about ± 1°F. The spurious responses set a limit on the sensitivity of the instrument, and it, therefore, appears that the probe will be effective in indicating icing conditions which produce about a 2°F temperature rise on the front element. The corresponding icing rate is a function of air speed, but as an example, at 300 mph an icing rate of 0.015 in/min would produce a 2°F temperature rise in the front element. This then is the minimum icing rate that the instrument could reliably detect at 300 mps. A second conclusion is that the angle of the front element is not very critical. The difference in response between the two probes is about the same as the difference in response between the runs with the same probe; and the probe with the 45° front section is perhaps the better. On the other hand, it appears essential to match the time constants of the two elements fairly closely. In the unmatched probe, Y, the transient output amounted to about 2°F when the wall temperature changed about 4°F. Since temperature changes considerably greater than 4°F will be encountered in flight, mismatched elements would produce spurious signals that would be confused with signals of icing. It further appears that Equation 13 is reliable for computing the balance of the time constants of the two elements.

Another observation made in the course of the tests deserves mention. There was always a large transient swing in the output of the instrument after the air in the tunnel was turned on. This was because the two elements were not initially at the same temperature. The convective heat transfer from the elements in still air is very small and especially so at small temperature differences. Consequently, if one element is heated by the touch of a hand or by radiation it does not immediately return to the air temperature. The instrument should not, therefore, be balanced or adjusted in still air.

GENERAL OBSERVATIONS

The following remarks, although not directly pertaining to the foregoing tests, may be of interest and assistance in the further development of the icing indicator.

As pointed out by Findeisen, the instrument should be located on the aeroplane in such a position that it is not affected by the thermal effects of the engines. It should also be located far enough from the wing and fuselage to be out of the boundry layer and out of the region where the drop content of the air is modified by the presence of the aeroplane. In general, these considerations argue in favor of locating the instrument forward in the plane and having the probe protrude several inches beyond the plane surface.

Findeisen also points out that solar radiation can heat the front element and thus give a spurious indication of icing. The spurious nature of such a signal will always be obvious to a pilot since it will occur only in bright sunlight when it is evident that there is no danger of icing. However, the confidence of the pilot in the instrument might be undermined if the device gives erroneous warnings. Use of the instrument with completely automatic ice-protection equipment would be difficult if spurious responses are encountered. In any case, the signal can be avoided by placing a radiation shield around the probe.

The probes used for the tests described above were constructed by machining the metal and plastic parts, inserting the thermistors and associated wiring in the elements, and then securing the parts together with screws. Although this method of construction was satisfactory for production of a small number of probes, it is likely that better methods can be found for production of larger numbers. One suggestion is that the metal elements, thermistors, and wiring be fabricated first in a unit and then the plastic part be cast around the unit by some suitable process, perhaps injection molding. A probe constructed in this way would not offer any access to the thermistors after it is once finished, but this does not seem to be a serious objection.

The probes used in the tests were about 4 inches long. This size was chosen arbitrarily and there is no reason to believe that it is critical. As a rule smaller probes react more quickly to changes in the icing conditions but are harder to work with and are more fragile. Another consideration is that the rate at which a body accumulates ice is a function of its size. This is because the very small drops of an icing cloud do not impinge on large bodies but do on small ones. The indicator probe will indicate the icing rate appropriate to its own size, and it appears desirable that its front diameter should be about the same size as the smaller parts of the aircraft such as antenna masts so that a direct indication is given of the icing rate on the most susceptible parts of the plane.

If an aircraft carrying the indicator probe flies for a considerable time in icing conditions, the instrument will become unusable because of the ice accumulation, and it will be necessary to remove the ice to restore the instrument to effective operation. It is difficult to conceive of any method for removing the ice accretion that does not involve considerable equipment, since any ice-removal system must be operated intermittently and, therefore, will require switching equipment. Furthermore, while the ice is being removed the signals from the instrument will not be indicative of the icing conditions, and will probably be temporarily disabled. These considerations do not preclude the possibility that a simple method of ice removal may be devised, but at present the prospects appear poor.

In contrast, the instrument without a deicing system requires very little equipment. If temperature-sensitive resistors are put in the elements and connected in a bridge circuit as was done in the experimental probes, the power for the bridge can be taken directly from the 24-volt D.C. supply of the plane, and the output of the bridge can be used directly to actuate a small meter that will give a rough indication of the icing severity. In addition or alternatively, the output of the bridge can be used in conjunction with a small rectifier to operate a light that will go on when icing conditions are encountered. The chief virtue of an instrument such as that proposed by Tribus and Moyle, in comparison to other icing indicators, is its extreme simplicity.

The most suitable use for the instrument appears to be on aircraft that do not expect to remain in icing conditions for extended periods. In such an application, it offers a very simple and inexpensive device that will warn the pilot when the plant encounters icing, and then give him an indication on a meter whether the maneuvers which he undertakes to escape the icing conditions are taking the plane into more or less severe icing conditions. When the plane emerges from the icing cloud, the ice on the probe will either melt or sublime.

Finally, it should be noted that the rear element of the probe has possibilities as a good thermometer for measuring the temperature of the air stream, since it is sheltered from impinging articles and has a recovery factor that is independent of velocity. An additional thermistor could be located in the rear element and its resistance used as a measure of the temperature. A correction for the speed of the plane would be necessary, but the correction would be simpler than for thermometric elements that do not have constant recovery factors.

CONCLUSIONS

Theoretical and experimental studies of the thermometric icing-indicator probe suggested by Tribus and Moyle indicate that the instrument can be designed to give a warning of icing and an approximate indication of the severity of the icing. The instrument will be unaffected by frictional heating at high speeds and only slightly affected by sudden thermal changes in the environment. The minimum icing rate to which the instrument will respond is somewhat a function of velocity, but the order of magnitude is about 0.015 inch per minute. The design criteria, which are given in the body of this report, are not critical and the instrument will operate satisfactority with reasonable manufacturing tolerances.

One of the chief advantages of this instrument is its extreme simplicity. However, the simplicity can be achieved only if it is not necessary to introduce equipment to remove ice from the probe of the instrument. The probe,therefore, appears most suitable for use in aircraft that do not expect to remain in icing conditions for extended periods.

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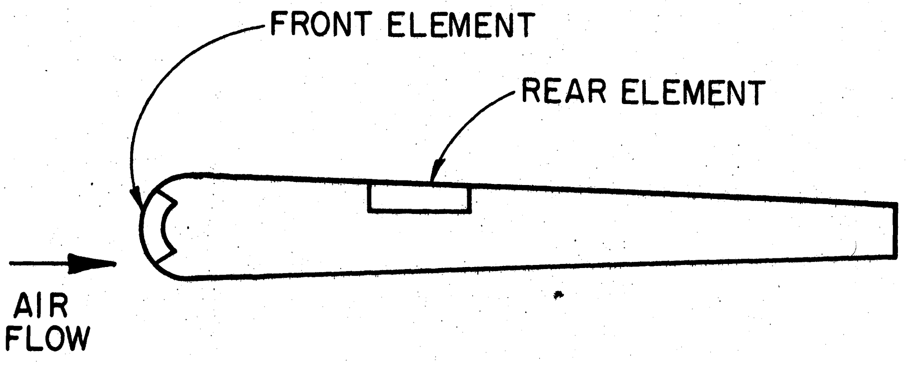

Fig. 1. Sketch of probe.

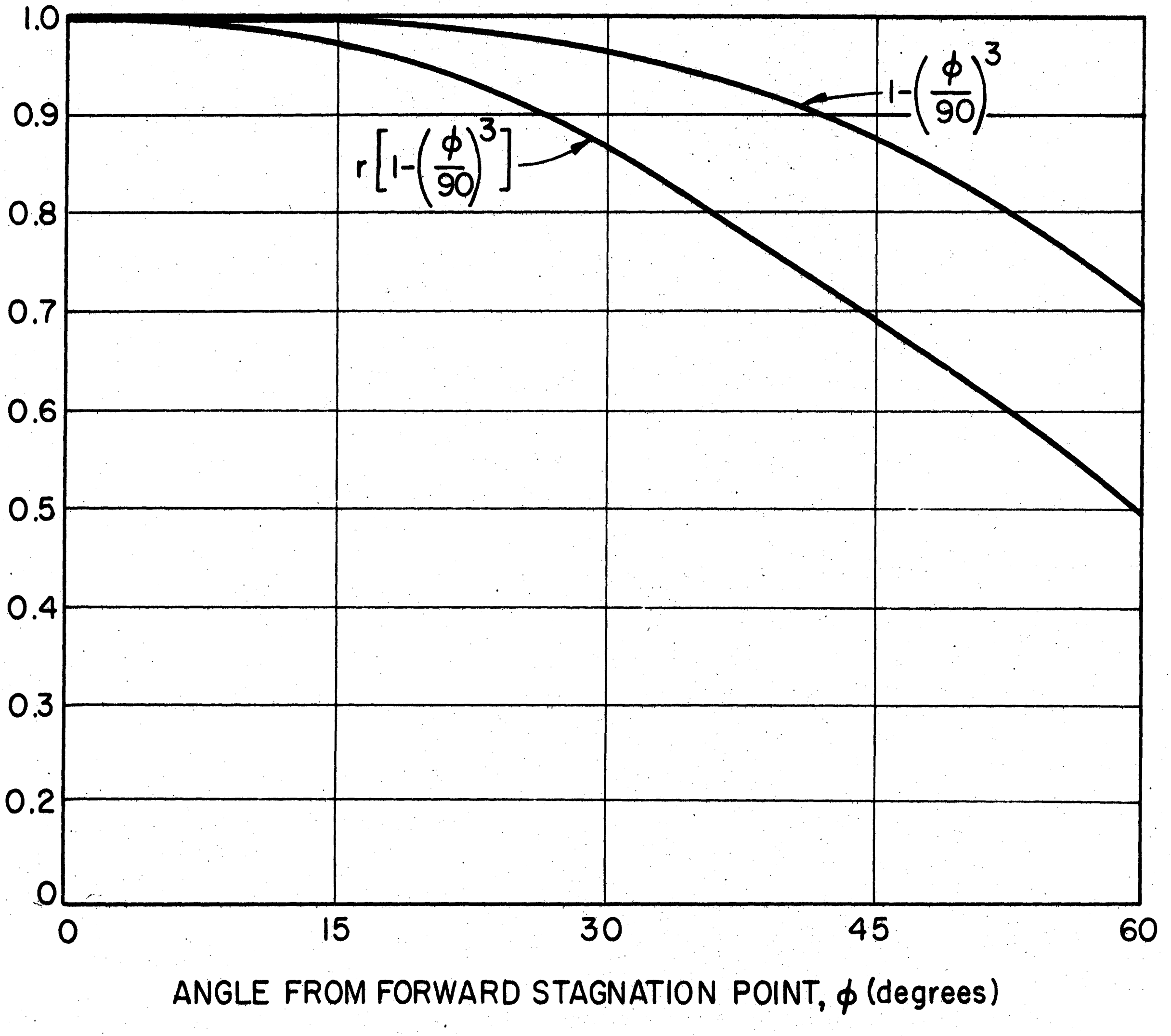

Fig. 2. Functions appearing in equation 5.

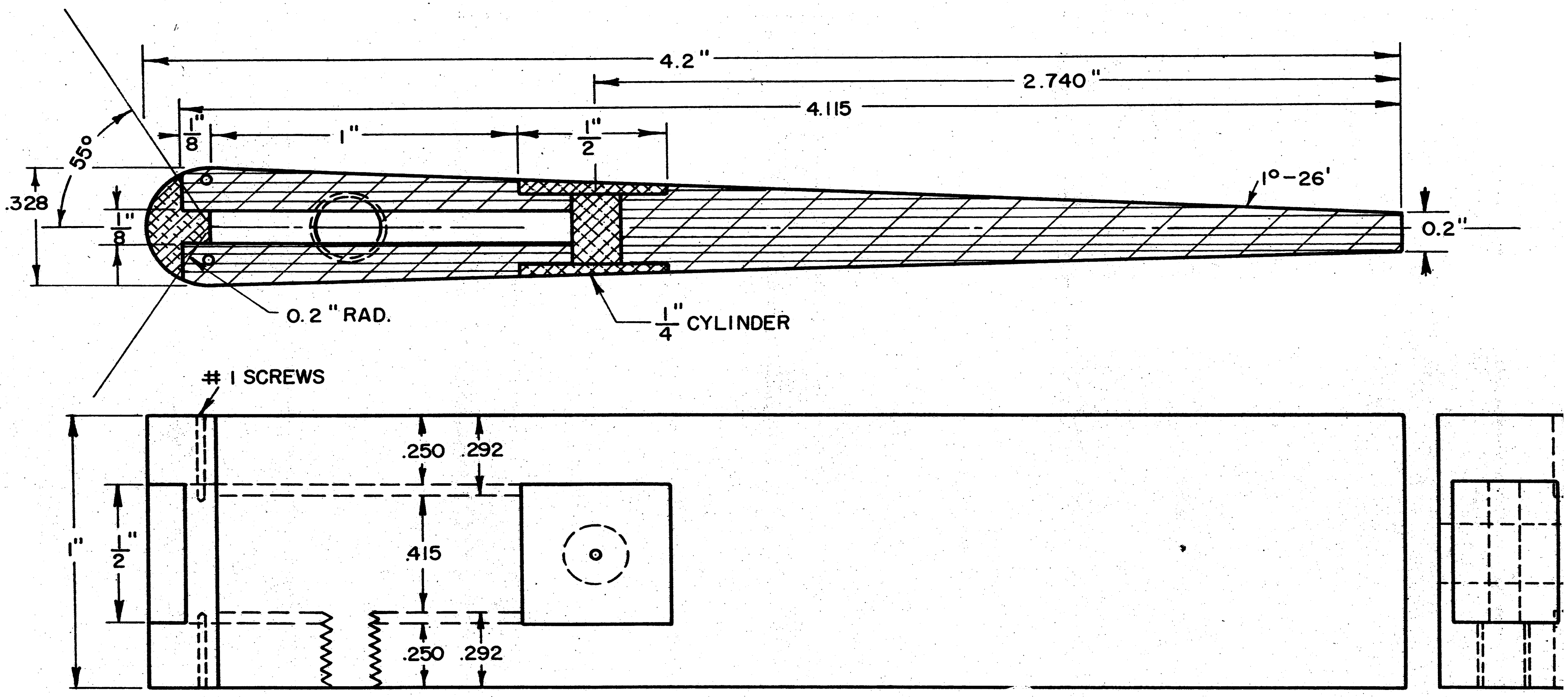

Fig. 3. Icing indicator probe.

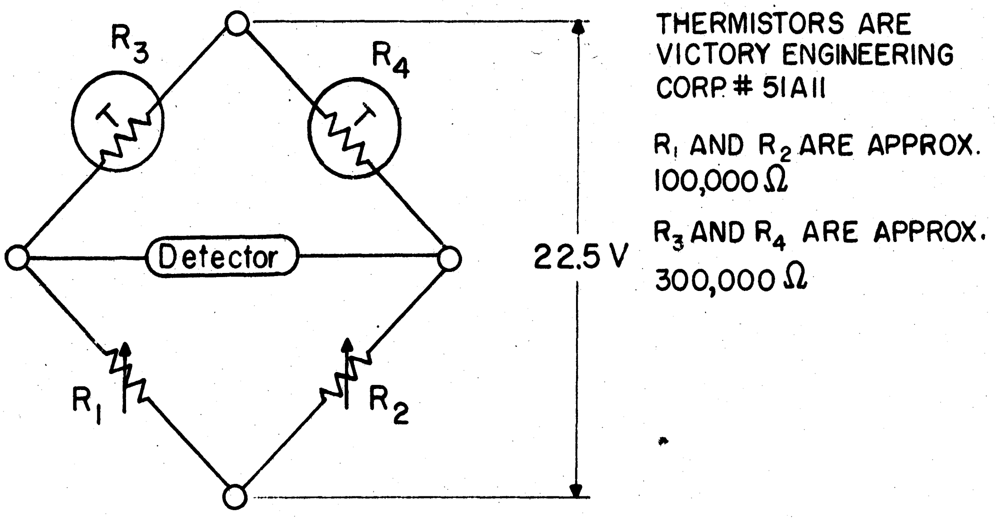

Fig. 4. Electrical circuit.

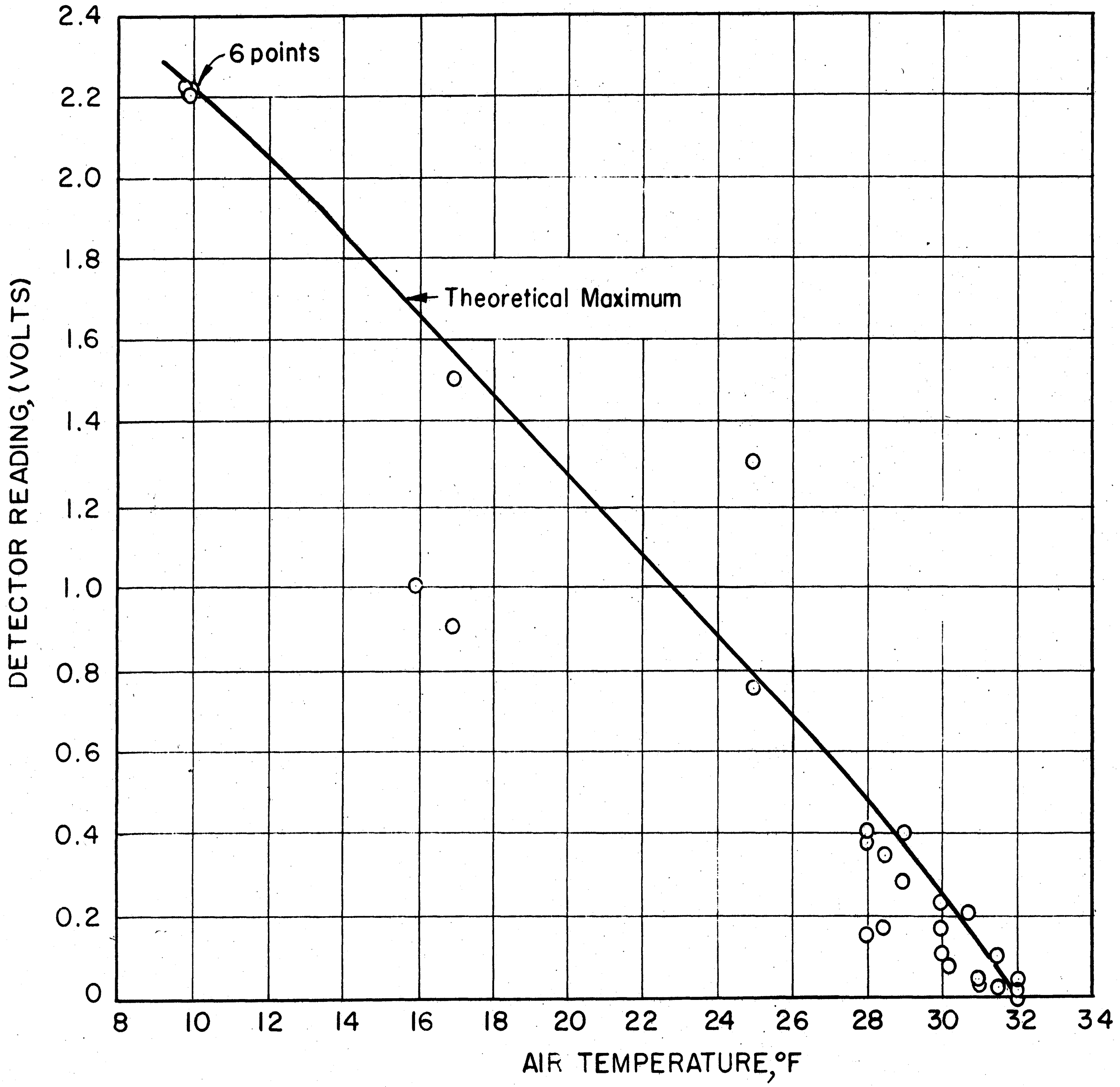

Fig. 5. Output of indicator probe in icing conditions.