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No. 905

TEMPERATURE-INDICATING PAINTS

By F. Penzig

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TECHNICAL MEMORANDUM NO. 905

TEMPERATURE-INDICATING PAINTS*

By F. Penzig.

It is often of importance to know the temperature distribution on the surface of a body. Point-by-point measurements consume a great deal of time; moreover, the measured values may be in error due to the conduction of heat or the change in the heat-flow conditions caused by the installation of the temperature-measuring apparatus. These difficulties may be avoided if the test body is given a coating of paint whose change in color** permits an estimate of the temperature. It is of particular advantage if the color persists after cooling because it is then possible to determine the temperature distribution in invisible machine parts after the test.

STATEMENT OF THE PROBLEM

In the investigations of fuels at the Oppau Works of the I.G. Farbenindustrie, A.G., it was found necessary for many years to conduct tests on air-cooled engines. For this purpose single-cylinder engines fitted with baffles were employed, to which the cooling air was supplied by a blower. In the course of the tests, deviations in temperature appeared as a result of modifications of the baffles and hence of the temperature distribution over the cylinders. The problem thus arose of investigating the temperature distribution at each cylinder in order to determine the effect of the various baffle shapes. Since the six thermocouples used for each cylinder were evidently not

*"Sichtbarmachen von Temperaturfeldern durch temperaturabhängige Farbanstriche." Z. V D I, vol. 83, no. 3, Jan. 21, 1939, pp. 69-74.

**Note.- In the original publication the different colors are shown on the figures. Since, in the reproductions of the figures, we are limited to black and white, the names only of the colors are used.

sufficient, it was first thought possible to obtain better results by the use of a large number of measuring points. Consideration, however, was taken of the fact that it is very difficult to install the thermocouples satisfactorily at the thin-walled cylinder and cooling fins without injuring these parts; at the same time considerable error is introduced in the measurements on account of the heat conduction to the wires. Besides, the space between the fins was blocked by the wires and the flow of the cooling air was thus hindered.

The foregoing considerations led to an attempt at an entirely new method, namely, that of coating the surface of the cylinder with materials that undergo chemical change at definite temperatures as indicated by a change in color. In this way it was hoped that the substance itself would indicate directly the position of its isotherms, which in measurements with thermocouples requires a tedious amount of labor.

The idea itself was by no means new, color coatings of this kind having been mentioned often in the literature on the subject (reference 1). The most familiar substances of this kind are double salts as, for example, mercuric-silver iodide $\text{HgI}_2 \cdot \text{AgI}$, which changes its yellow color into orange at 45°C . and mercuric-copper iodide $\text{HgI}_2 \cdot \text{CuI}$, which turns from red to black above 70°C . There are also various arsenic, antimony, and lead compounds. These materials, however, were not suited to our investigations because on cooling they return to their original color. This result is of advantage for the usual employment of these colors as warning signals but not for the investigation of parts which cannot be viewed during operation, as in the case of the tightly baffled cylinder. Moreover, since the tests were conducted on parts with complicated structure, it was desirable to be able to determine the temperature distribution for some time after the end of the test. The necessity thus arose of finding paints that should possess the following characteristics:

1. The original color should not return after cooling.
2. The colors above and below the color change should be clearly differentiated from one another.
3. The change in color should occur at a point as sharply defined as possible.

By the requirement of sharply differentiated colors, it was meant that color changes such as white to yellow, yellow to brown, and light green to dark green were to be excluded as unsuitable, since in operation on the test stand, slight color differences cannot be distinguished on account of the soiling of the parts by the oil. It was therefore desired to obtain marked color changes, as, for example, red to blue, yellow to red, green to brown.

A property soon recognized as very important was the sharp transition from one color to the other. Intermediate shades will always occur to some extent, since the color change is associated with chemical processes which, although occurring at a definite temperature, are initiated within a small temperature interval. This interval within which the color change occurs is smaller the higher the transition temperature. It amounts to only a few degrees, so that it is always possible to recognize the unique position of the isotherms.

The question was also considered whether, in contrast to these sharp transitions, it would not be better to attempt to find a coating with a uniform change of color with temperature, which would thus be determined at each point. Aside from the difficulty of producing a material with this property, practical considerations soon showed that difficulties are encountered in evaluating intermediate shades. It becomes necessary to determine the temperature with the aid of a calibrated color scale and then to draw in the isotherms.

CHARACTERISTICS OF TEMPERATURE-INDICATING PAINTS

Permanent paints for rendering temperature fields visible, such as mercuric sulphate, mercuric iodide, lead carbonate, cadmium carbonate, and others, have been applied in various ways. None of these materials, however, could sufficiently satisfy the above-described requirements, because the sharpness of the transition, the colors, and the unique correspondence of temperature to color change (reproducibility) were not satisfactory.

In order to attain any progress, it was necessary to conduct comprehensive and laborious development tests at the research laboratory of the Oppau Works; this work led to the use of entirely new materials. These paints, which

were designated by the term "thermocolor," are metallic salts that liberate water, carbon dioxide, ammonia, etc. at definite temperatures and simultaneously change their colors. The extent of the difficulties encountered may be realized from the fact that, of the approximately 300 compounds investigated, only those given in table I proved practicable.

Table I

Colors and Temperatures of Thermopaints

No.	Color changes	Temperature	
		°C.	°F.
1	Rose to blue	30	90
2	Pale green to blue	60	140
3	Pale yellow to violet	110	230
4	Purple to blue	140	280
5	White to greenish brown	175	350
6	Green to dark brown	220	430
7	Yellow to reddish brown	290	555
8	White to light brown	340	645
9	Violet to white	440	825
20	Pale rose to light blue	65	120
	Light blue to light brown	145	290
30	Light green to light blue	65	120
	Light blue to olive green	145	290
	Olive green to grayish brown	220	430
31	Brown to grayish brown	155	310
	Grayish brown to greenish brown	230	450
	Greenish brown to reddish brown	275	530

The paints whose colors are given in figure 1 satisfy most of the requirements. On the basis of the work done, however, there seems to be possibility of supplementing and extending the color series at various points.

Paints with Several Color Changes

At first, isotherms were obtained by coatings having a single color transition. Later it was found possible to

obtain coatings with several transition points. This result was attained partly by the choice of substances that undergo successive chemical changes at various temperatures and partly by the mixing of simple colors. Those paints having several transition points proved to be very useful for obtaining a clear idea of the temperature distribution over a relatively wide range. Paints with single transition points were used to investigate definite temperature ranges, which were not indicated by multiple colors.

Accuracy of the Transition Point

The measuring accuracy for this chemical process is naturally not so great as for a physical process: it amounts to about 5° C. The object of the color coating is not, however, to replace accurate temperature measurements by means of thermocouples, but rather to give rapid information on the temperature distribution. Experience has shown that, in very many cases, it is sufficient to know the temperature distribution and thus the position of unfavorably high or low temperatures on a body. If the accuracy by this method is not sufficient the accurate temperature at positions of particular interest may be determined by means of thermocouples.

A property of the chemical process not to be overlooked is that the indications depend somewhat on the duration of the heating exposure. Measurements have shown that lower temperatures correspond to longer heating. These relations are shown in figures 2 and 3 and from them there may be determined the significance of the transitions for various heating exposure times. Little use was made of these, however, since the tests were mostly comparisons under the same conditions.

Furthermore, it is a property of the paints 1, 2, and 3 (table I) that they slowly return to the original color under the effect of air humidity and more rapidly on wetting with water. This characteristic permits the repeated use of the same paint and so may be useful for some purposes, but it is planned to develop further paints in the region of lower temperatures. Meanwhile, where it is important that the color change persist indefinitely, paints 20 and 30 are used, giving the first color transition at 65° C.

Applying the Paints

An important part of the development work was concerned with the choice of the binding material. Slow-drying coatings were unsuitable. Therefore a synthetic resin soluble in alcohol was chosen as a binding material. The alcohol evaporates in a few minutes and the paint thus dries rapidly. The synthetic resin dissolved in the alcohol was originally used as a liquid binding material but later it was finely pulverized and added to the color powder, so that a coating ready to be applied was obtained by mixing with alcohol. This process at the same time has the advantage that the viscosity of the paints can be adjusted at will and the coating thus applied with either brush or spray gun.

The coating is resistant to gasoline and oil. The nature of the paint excludes its application where water is encountered. In the case of gases which differ considerably from air by their content of water vapor, carbon dioxide, ammonia, sulphur dioxide, and hydrogen sulphide, it is necessary to take account of the effect on the transition temperature, the magnitude of which effect must be determined for each particular case.

Binding materials of organic nature indefinitely resistant to temperature are unfortunately unavailable. For this reason the synthetic resin was chosen with the consideration in mind that it causes no discoloration at high temperatures. This property is very important since fat oils, for example, turn yellow at temperatures above 100° and finally are blackened so that the clearness of the colors is impaired. The coating also adheres very strongly to its base at high temperatures at which the binding material is destroyed. Therefore, in the proposed development of temperature-indicating paints, no difficulties are to be expected up to 650° C.

Effect of the Paint on the Heat Transfer

No apprehension need be felt that the paint interferes with the heat transfer from the body to the air. Motor-vehicle radiators often have a protective coating on the air-exposed side, and heating bodies are often lacquered. It follows, therefore, that the effect of the paint layer is, at least, not considerable. The following consideration shows that it may even be neglected.

If, for example, the heat conduction through the walls of an air-cooled coated cylinder and the heat delivered to the surrounding air are considered, heat resistance W of the arrangement may be taken as the sum

$$W = W_1 + W_2 + W_3$$

where $W_1 = d/\lambda$ is the resistance of the wall of thickness d , assumed as 3 mm, and λ the heat conductivity, for iron = 50;

$W_2 = d'/\lambda'$, the resistance of the color paint, assuming $d' = 0.1$ mm and $\lambda' = 1$;

$W_3 = 1/\alpha$, the heat transfer from the surface to the air where α has a value of 15 to 75 depending on the air velocity; here it is assumed that $\alpha = 50$.

From the assumed values there is obtained $W = 0.00006 + 0.0001 + 0.02$. The resistances are in the ratio 0.6 : 1 : 200. The heat transfer to the air thus represents such a large resistance that, in comparison with it, the resistance of the color paint is quite insignificant even if its thickness were several times the value assumed. Actually a thickness of the coating from 0.03 to 0.07 mm is sufficient.

It is also entirely permissible to paint the colors over existing coatings and lacquers. At times several thermocolor coatings were applied one on top of the other. It is always worth the small trouble of first cleaning the substance with a steel brush or sandblower, however, in order to obtain a well-appearing and fast-adhering coating.

APPLICATIONS

Investigations of Air-Cooled Engines

In the investigation of air-cooled cylinders on test stands the coated cylinder was operated under fixed conditions. At the end of the test it was necessary to see that the heat conducted away was always greater than the heat received. If this fundamental rule was violated, for example, by stopping the cooling too early, transfer of heat would occur from the warmer to the cooler parts, and this temperature equalization would thus disturb the temperature distribution obtained in actual operation.

The manner in which the temperature fields were investigated by means of the temperature-indicating paints is shown in figure 4. The cylinder investigated is that of an airplane engine type BMW 132. A blower delivered the air to a baffled cylinder. The latter was covered with various temperature-indicating paints, the barrel with thermocolor 4, the exhaust side of the cylinder head with thermocolor 7 and the inlet side with the triple-change paint 30.

The color transition on the barrel shows that on the sides the temperatures lay below 140° C., so that the red base color was unchanged. On the downstream side the air velocity was too small, the temperature of 140° C. was exceeded, and the color changed to blue. On the exhaust side of the cylinder head, it is seen where the temperature was 290° C. and more from the transition of paint 7 from yellow to reddish brown. The reddish-brown color is found at the exit passage at the back. It is immediately evident that, at the exhaust, more effective fin area would be desirable. The color coating 30 on the inlet side shows clearly that, in this test, the rocking lever bushing did not heat up above 65° C. since the color remained light green. Toward the combustion space the color is light blue, which persists to 145° C. The cooling fins show by their olive-green color that they are warmed above 145° C, but not above 220° C. The temperature of 220° C. is first attained in the neighborhood of the spark-plug orifices, where there are no cooling fins, as indicated by the transition to greenish brown.

The visualization of the temperature fields makes it possible to follow a given process by color photography. It is also possible, however, to apply black and white photography and mark the isotherms on the picture by hand. Thus figure 5, for example, shows the position of the 140° C., 175° C., and 220° C. isotherms on the barrel of an airplane-engine cylinder. At the same time, this figure affords an example of the application of several paints inasmuch as the cooling fins were coated in succession with thermocolors 4, 5, and 6. After the tests, the transition points were marked by glued-on paper disks, and the cylinder was then photographed. The three isotherms were obtained by joining the corresponding color transition points.

The investigations on air cooling were carried out by varying the shape and the position of the baffles until the desired temperature distribution was obtained. The re-

sults of such tests, which require only a short time, are given in figures 6 to 14. The shape of the air passages is indicated in figures 9 to 11. For a simple body such as that of a cylinder barrel, a clear picture of the temperature distribution can also be obtained by drawing the isotherms as shown in figures 12 to 14.

It is readily seen from the curves that the changes in the air-passage shape led to the following results. Directing the cooling air on one side without baffle sheets (figs. 6, 9, and 12) leads to considerable temperature differences between the exposed and the screened sides of the cylinder. Although the cylinder was only moderately loaded, as indicated by a region of the cylinder head with temperatures below 65° C., the barrel shows a very wide region above 140° C., which doubtless also includes temperatures above 220° C. as indicated by the position of these isotherms on the cylinder head. As shown by figure 12 this range nevertheless contains a small and somewhat indefinitely bounded region of temperatures below 140° C. Apparently at this region higher velocities and hence better cooling were induced by turbulence.

The second baffle arrangement (figs. 7, 10, and 13) leads to good air conduction over the down-wind side. At the edges, however, the air velocity between the fins drops on account of the widening in cross section so that two strips of higher temperature arise. If the baffling is made tighter on the down-wind side (figs. 8, 11, and 14) better cooling is obtained.

After some experimenting with the temperature-indicating paints this process was applied to a wider range and found to be of greater interest than had been originally supposed. It was just in the field of air-cooled engines that an aid of this sort was very much in demand. By means of this new process it is now possible for the engine constructor to see immediately, without inconvenient measurements, where more fin area or improvement in the baffling is required and how successful his modifications are. There is a great advantage also in being able to make the proper adjustment of the baffles and insure the uniform operation of the cylinders with greater simplicity and lower cost than was heretofore possible.

Air-cooled engines, and particularly airplane engines, set high requirements on the fuels with regard to their resistance to knock. This requirement is due mostly to

the large and undivided combustion chambers and the high continuous loading of these engines during which the walls and valves assume high temperatures. With better control of the cooling, either lower knock rating may be required of the fuel or a higher output is possible by overloading.

Temperature Measurement at the Piston

A particularly interesting application will be found also in connection with the measurement of the piston temperatures. For this purpose plugs of alloys of various melting points are often placed in holes inside the piston and the temperature of the piston determined from the melting points. Only a large number of measuring points, however, can give a sufficient indication of the temperature. Moreover, the weakening of the parts by the holes and the possible disturbances from the melting metal may lead to undesirable results. An attempt was made therefore to apply the temperature-indicating paints for measuring the piston temperatures, although here the conditions are considerably more difficult than for an air-exposed surface. It was found, however, that the binding material of the color was completely resistant to the hot engine oil, although for tests of some duration, the black deposit from the oil covered the color coating. In a comparative investigation of several types of pistons, however, it is always possible to limit the testing time to about one-half hour, so that no large deposits are formed and, after washing the piston with benzene, the colors on the inner side of the piston may be readily distinguished. In this case, too, care must be taken to see that no temperature equalization takes place after the test. In some tests, the formation of deposits could not be avoided, but by careful cleaning with emery the coating may again be exposed. Figure 15 shows the temperature distribution at the pin bearing of an airplane-engine piston. The heat flowing in at the piston head flows off at least partly through the piston grooves to the cylinder walls. In the neighborhood of the pin bearing, this path is interrupted. The heat must then flow off from the piston pin for which a considerably higher temperature drop is necessary. The 220° C. isotherm in this test therefore runs from the upper ends of the grooves diagonally downward to the pin. It was also possible to show in this test that the piston was considerably cooler on the upstream side than on the opposite side.

In investigations of the small end of the connecting rod, it was found that the heat of the piston was conducted away not only through the piston pin but evidently to a considerable extent by radiation and oil spray.

Automobile Parts and Engines

Of the numerous fields of application for the temperature-indicating paints, there may be named those in connection with the engine construction for vehicles: the investigation of exhaust collectors, exhaust pipes and mufflers, measurements on apparatus, such as ignition during operation, investigations on couplings, brake drums, and brake linings.

Temperature Distribution over Heating Apparatus

Investigation has been made of heating apparatus (fig. 16) for which it is desirable that the entire surface have as uniform a temperature drop to the air as possible. It was found that, in the case of electrical heating bodies, the ribs are not entirely effective in the heat transfer. Investigation also showed that the circular ribs often employed do not represent the best possible shape. In pipes of this kind, which are situated horizontally in the free air, a temperature distribution on the rib was obtained of the kind shown in figure 17. The isotherm, in this case 220° C., runs rather close to the pipe at the bottom, while on top it leaves the rib surface. A more uniform temperature loading is obtained by the rib shape shown in figure 18, which is adjusted to that of the isotherm and requires less material. These questions, which have also been considered in the literature on the subject, illustrate that, with the aid of temperature-indicating paints, it is very simple to carry out investigations which up to now have been very difficult. Saving in material, which may be considerable in mass production, can doubtlessly be made in this way.

On the basis of investigations of the temperature distribution on gas-heated plates, it has already been pointed out by E. Schunacher (reference 2) that investigations need to be made on present-day heating plates with regard to material, size, thickness, arrangement of ribs, etc. Unquestionably household economy may be effected in the heat sources employed by improvement in the temperature

distribution. The temperature distribution on heating plates of a kitchen heater is shown in figure 19.

In driers and annealing furnaces, the method has already been successfully applied. By color painting the objects investigated, it was determined whether the desired temperatures were actually attained. A temperature measurement itself at several positions in the oven space was shown to be insufficient, since the temperature distribution as obtained by these measurements is remarkably non-uniform in large chambers, and temperature differences of 100° C. may easily arise. In investigations of this kind the objects must be observed through observation holes because on removing the substance, it would receive on its surface the highest temperature that it encounters. The application of this method for stressless annealing and tempering cast-light-metal pieces will undoubtedly result in a more uniform condition of the pieces.

Protection Against Inadmissible Temperatures

The temperature-indicating paints have, in the meantime, also found application in electrical technology. They are particularly important in this field of application because, with the aid of these colors, information may be obtained in cases of injury and insurance claims thus proved. In injuries to electrical apparatus and machines it is often difficult for the manufacturer to determine whether the fault was to be ascribed to a structural weakness or to overloading. In order to clarify this point, the rotor of a synchronous motor, for example, is provided with a strip of temperature indicating paint. If injury occurs to the stator coil, it is easy to determine from the color on the rotor whether there was overloading or not.

In the construction of piping and tanks, reverting paints for indicating inadmissibly high temperatures have long been in use. In many cases, however, it is convenient to use paints that do not revert to their original colors in order to be able to investigate later the causes of temporary overheating. Thus, for example, lack of tightness in the steam pipe may be discovered in time. It should also be useful for indicating injuries in brick-lined vessels by change in color. By painting a warning on the wall in the basic color, the warning remains invisible at low temperatures and suddenly appears when the transition temperature is exceeded (fig. 20).

Temperature-Indicating Paints for Instruction Purposes

In conclusion, there may be pointed out the use of these colors for instruction purposes. Thus the conductivity of metals may clearly be demonstrated by coating strips with these colors. The processes and heat flows in riveted or welded joints can also be made visible to a large audience with the projecting lantern.

Translation by S. Reiss,
National Advisory Committee
for Aeronautics.

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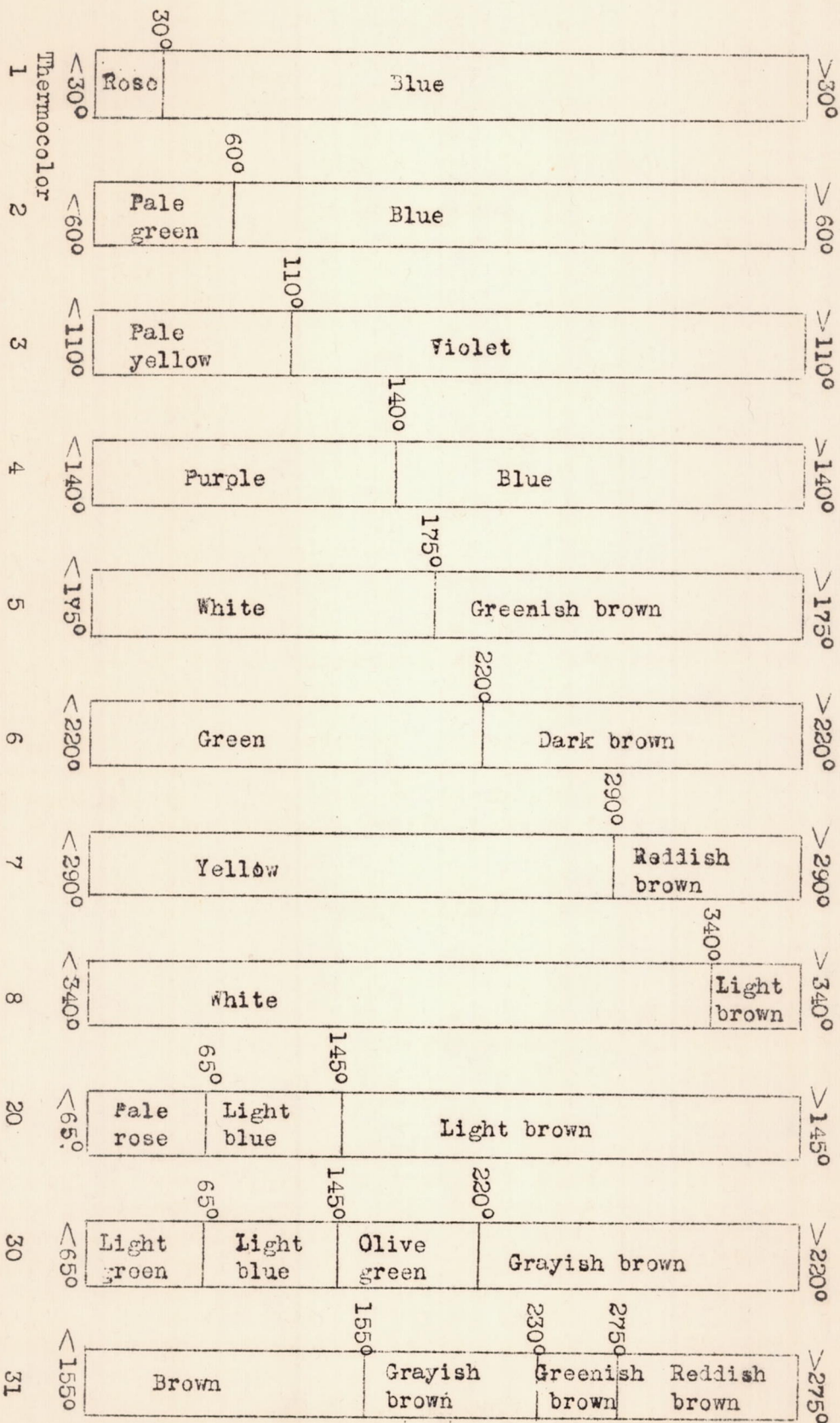
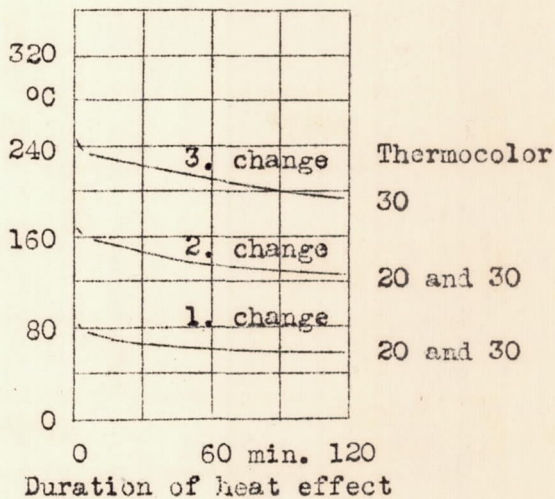
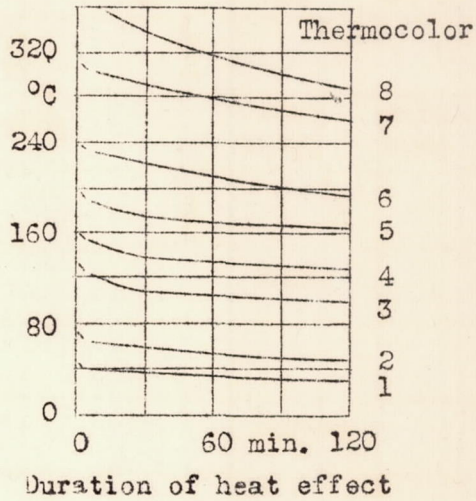


Figure 1.- Temperature-indicating paints thus far developed.



Figures 2,3.-- Relation between the temperature recorded and the time of exposure.

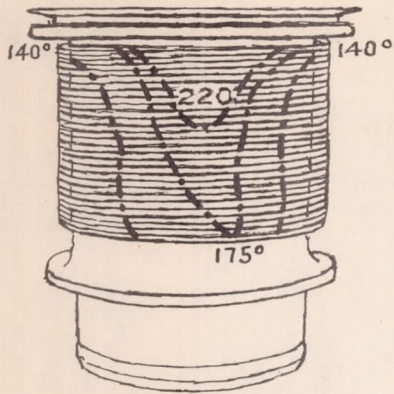


Figure 5.- Temperature distribution over the barrel of an air-cooled airplane-engine cylinder. The cooling fins were coated in succession with thermocolors 4,5, and 6. After the test the positions of temperature change were marked by small paper disks and the photograph obtained. The 140°, 175° and 220° C. isotherms were then readily obtained.

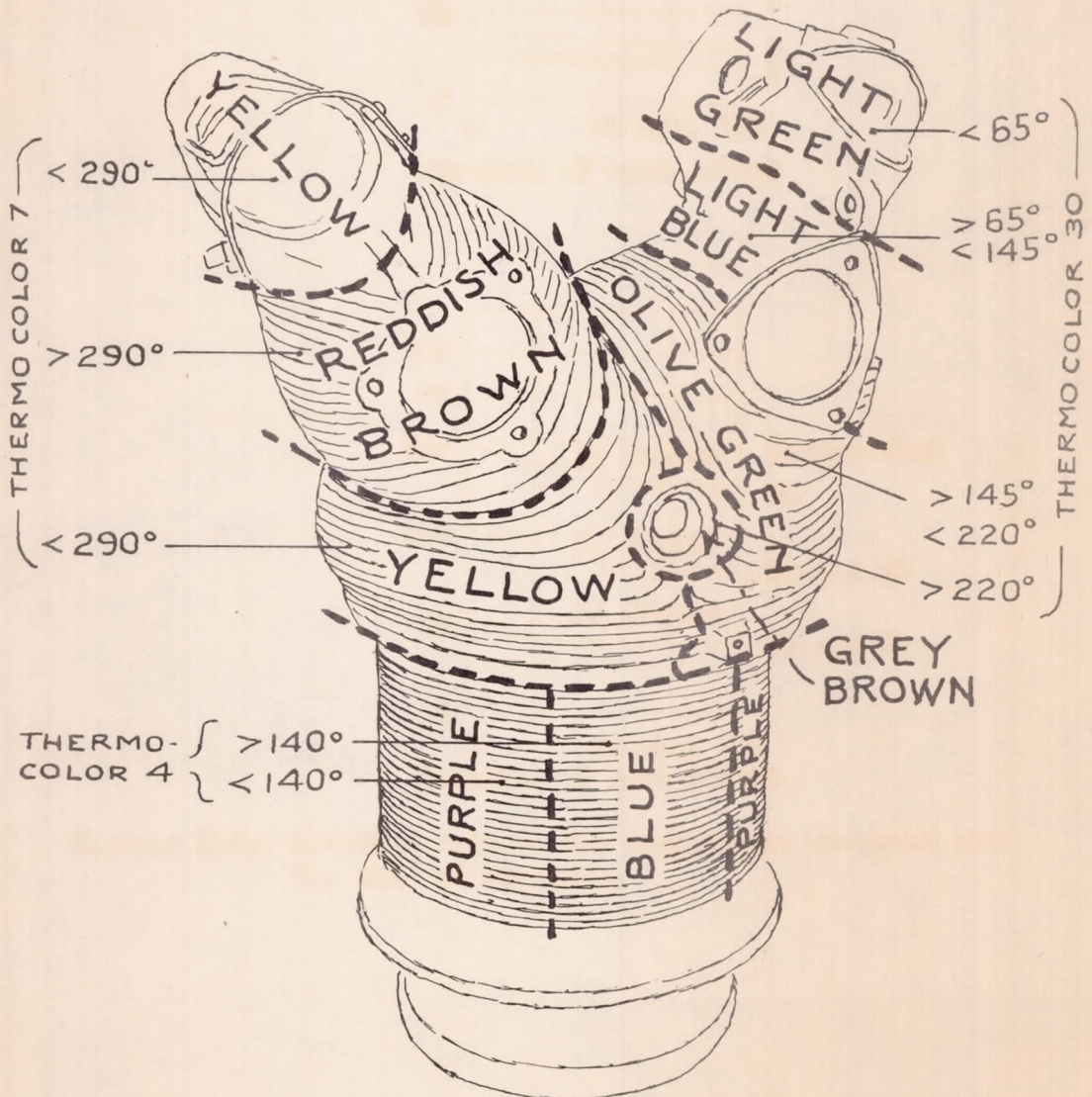
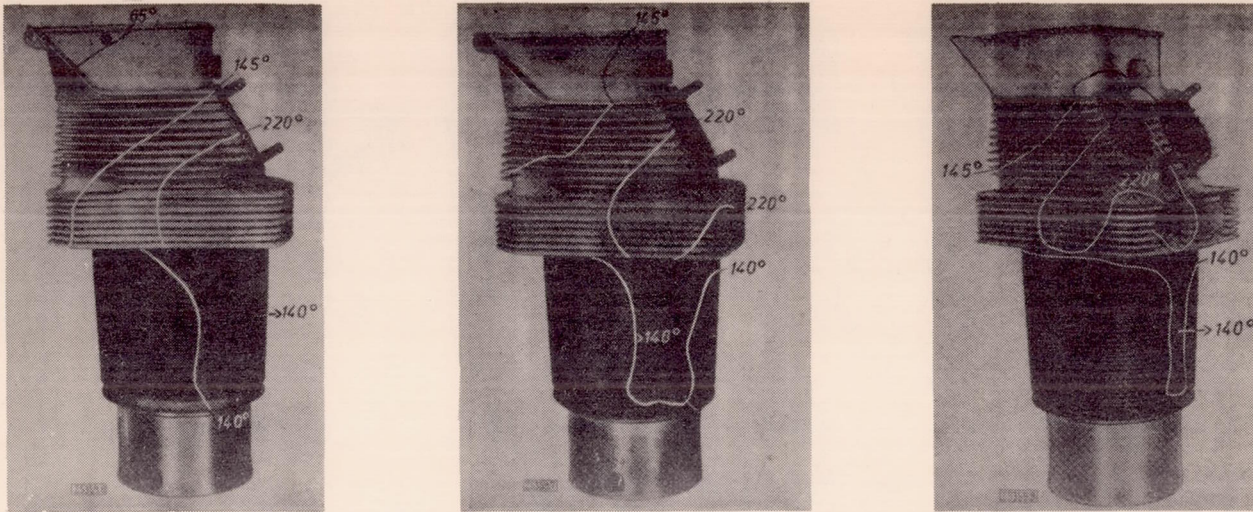
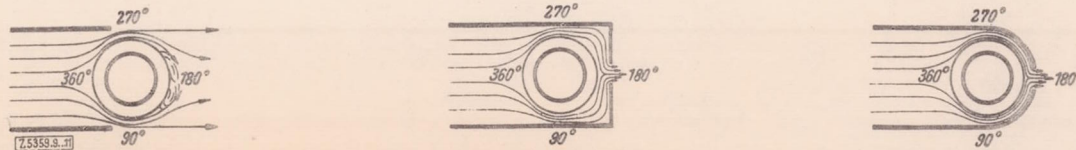


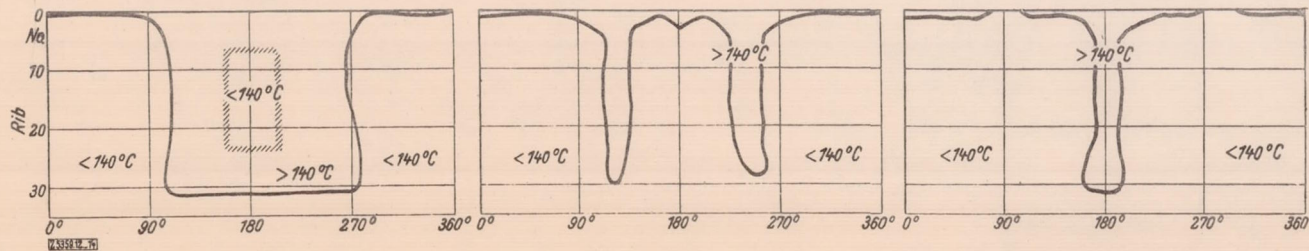
Figure 4.- Temperature distribution over an air-cooled airplane-engine cylinder.



Figures 5 to 8.- Positions of the isotherms on the cylinder. Investigated with thermocolors 30 and 4.



Figures 9 to 11.- Effect of baffle arrangement on the air flow.



Figures 12 to 14.- Temperature distribution over the lower half of the cylinder.

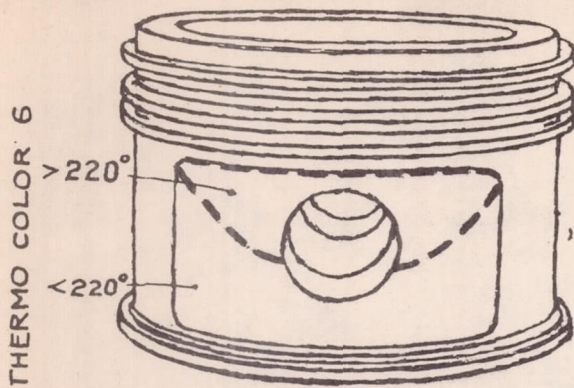


Figure 15.- Temperature distribution over the pin bearing of a piston, measured with thermocolor 6. In the neighborhood of the bearing the heat conduction is lowered by the piston grooves. The heat loading of the pin bearing is therefore high for this particular piston.

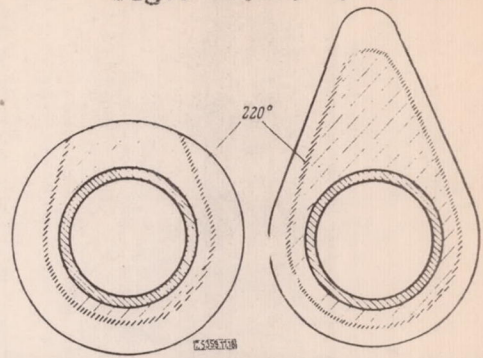


Figure 17 and 18.- Adjustment of the rib shape of a heating tube to the shape of the isotherm. The circular shape gives a nonuniform temperature drop to the air. By the adjustment of the rib shape to the isotherm, a saving in material may be obtained.

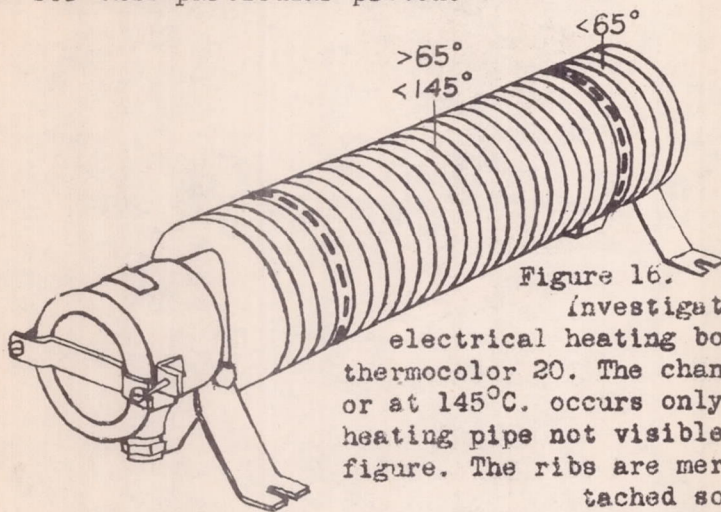


Figure 16. Investigation of an electrical heating body with thermocolor 20. The change in color at 145°C. occurs only at the heating pipe not visible on the figure. The ribs are merely attached so that at the transition between the pipe and the ribs there is a considerable temperature jump.

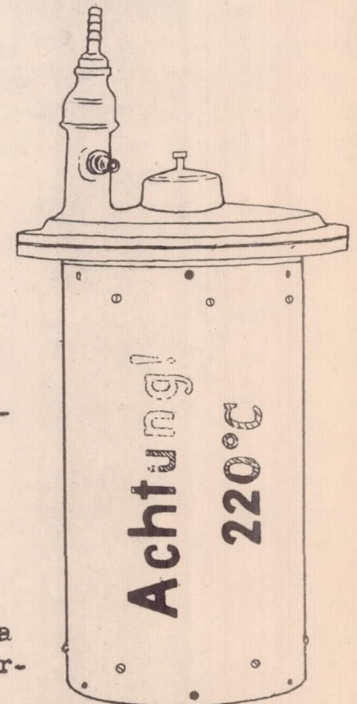


Figure 20.- Warning sign that appears at 220°C. The warning sign was painted with thermocolor 6 over a basic point of the same color and is almost invisible but clearly appears as soon as the temperature of 220°C. is exceeded.

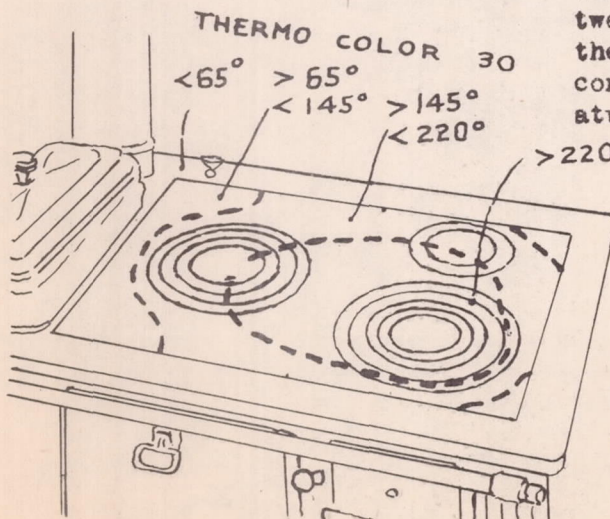


Figure 19.- Temperature distribution on an oven plate measured with thermocolor 30. The temperature is distributed sufficiently uniformly over the three heating positions.