A PHYSICAL STUDY OF THE WELSBACH MANTLE.*†

BY

HERBERT E. IVES,

Ph.D., Captain, S. R. C., U. S. A.

E. F. KINGSBURY,

Ph. D., Lieut., S. R. C., U. S. A.

AND

E. KARRER,

Ph.D., Private, U. S. A.

Members of the Institute.

VIII. MANTLES COMPOSED OF OXIDES AND MIXTURES OF OXIDES OF HIGH EMISSIVE POWER IN THE VISIBLE SPECTRUM.

I. Thoria-Ceria.

The series of mixtures of thoria and ceria, in which is included the Welsbach mantle of commerce, is in many respects the most interesting of the mixtures studied. In it are exhibited in striking manner the characteristics of an optimum proportion of the constituents, a fundamental difference in the optical properties of the hot and cold mantle, and a greatly different behavior under different kinds of heating. A full discussion of this series therefore covers many of the characteristics found in others, which can, in their turn, be described briefly in terms of their likeness or unlikeness to the thoria-ceria mixtures.

Gross Physical Characteristics.

Pure thorium oxide, ThO_2 , is white, of high reflecting power (85 per cent.), and does not show any color change on heating in a quartz tube in the Bunsen flame. Pure cerium oxide (CeO_2) is either white or brownish white, depending on the method of preparation. Both varieties turn deep yellow or brown in heating to a few hundred degrees, a characteristic which persists in the mixtures of ceria with thoria to very low percentages of the former. It is exhibited clearly in the regular commercial mantle (approximately 1 per cent. ceria) when this is turned low.

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The mantles for study were made of silk. The pure thoria mantles had a weight of 0.009 gramme per cm.², the pure ceria of 0.0097 gramme per cm.²

Temperature.

The relationship between constitution and temperature is shown in Fig. 16 (VI) for these mixtures. A point of importance appears at once from these curves, namely, the possibility of two adjustments: (1) The adjustment which would be made from

FIG. 16.

- Properties of thoria-ceria mixtures:
- I. Spectral distribution of emission.
 - II. Spectral distribution of emission, visible region.
 - III. Emission constitution relation, isochromatics.
 - IV. Radiant luminous efficiency—constitution relation.
 - V. Radiance—constitution relation.
 - VI. Temperature—constitution relation.

the standpoint of light-production—that is, the adjustment of maximum luminosity; and (2) that which would be made if one wished the maximum of radiant heat. The first adjustment is with the flame just inside the mantle; the second is with the flame coming through and enveloping it. In the pure ceria mantle the difference is most striking. As the flame is turned up the mantle gains in brightness until a certain point, when, as the flame strikes through, the light drops off as though quenched by a suffocating gas. This happens first at the top of the mantle,

leaving a bright ring in the bottom, and then with a still larger flame the whole mantle goes dull. As is shown by the curves, and in accordance with the temperature radiation relationship discussed above, the temperature is much lower for the condition of maximum radiation. This different behavior does not appear in the pure thoria mantle, but is a characteristic of the ceria constituent, and will be discussed in greater detail later. The temperature range between the pure thoria and the pure ceria is

FIG. 17.

Emissive power characteristics of thoria-ceria mixtures:
 I. Spectral distribution of emissive power.
 II. Spectral distribution of emissive power, visible region.
 III. Constitution—emissive-power isochromatics.
 IV. Total emissive power—constitution relations.

about 400° (1930° – 1500°) for the condition of maximum luminosity, and about 600° (1930° – 1340°) for maximum radiation. The fall in temperature is most rapid for the low percentages of ceria.

Total Radiation and Emissive Power.

The variation in total radiation with constitution is shown in Fig. 16 (V) for both adjustments, and in Fig. 17 (IV) is given the variation in emissive power.

The radiant emission of the pure ceria mantle is nearly twice that of the pure thoria for the condition of maximum luminosity, and more than twice for maximum radiation. As with the temperature changes, the increase in emission is much more rapid for the smaller admixtures of ceria than later.

The emissive power of thoria, as previously noted, is exceedingly low, about 4 per cent. For the adjustment of maximum luminosity the rise of emissive power is rather gradual, up to 22 per cent. for pure ceria. For maximum radiation it is more rapid for the smaller percentages of ceria, reaching a maximum value of 40 per cent.

Both the behavior of the emission and the emissive power will be analyzed in the discussion of the spectral distribution curves. It is to be noted, as a general criticism of all the emissive power data, both the total and the spectral distribution, that the widely different temperatures and radiating characteristics with various adjustments make the figures given subject to very large possible errors, and the values shown for plotting are not in every case as entirely consistent with each other as could be desired.

Radiant Luminous Efficiency.

In Fig. 16 (IV) is shown the variation of radiant luminous efficiency with constitution. The general characteristic of mixtures of low and high visible emissive powers is shown; namely, the optimum for a certain low percentage of the blacker substance. In this case this maximum efficiency (0.0043) for the whole mantle is over three times that of a black body at the same temperature, the latter being shown by the lower line of the diagram, and occurs for a very small percentage of ceria (0.75 per cent.) and a high temperature (1900°). (For the brightest part of the mantle, through the 1 cm. diameter aperture, the efficiency is about 0.009.) This advantage over the black body persists through all the mixtures, although the difficulty of measuring the very low efficiencies of the ones rich in ceria, and the uncertainty in the corresponding temperatures, prevent a reliable quantitative estimate of the extent of the advantage in their case.

This curve of radiant luminous efficiency merely exhibits the well-known candle-power-ceria content relationship, giving no explanation of the very high value of efficiency attained. The reason for the exceedingly high value is given by the analysis represented in the spectral distribution curves.

Spectral Distribution of Emission and Emissive Power.

The spectral distribution of radiant emission is shown both for the visible and the infra-red regions in Fig. 16 (I and II), while Fig. 16 (III) exhibits the isochromatics or variations of the emission for selected individual wave-lengths.

The significant feature of these emission curves is the practically uniform and continuous increase of emission with ceria content in the infra-red region, and its initial very rapid rise to a maximum for 0.75 per cent. ceria and subsequent fall in the visible region. This feature is clearly presented by the isochromatics (III).

When it comes to the emissive power, the behavior is somewhat simpler. Emissive power increases at all wave-lengths with increasing ceria. In this case the significant feature is the rate of increase of emissive power with ceria content at the various wave-lengths (III). While for the infra-red wave-lengths the rise is uniform and gradual for the visible region, and particularly in the blue, the rise of emissive power is very abrupt, reaching saturation for a very low percentage. Not only this, but the actual emissive power attained is very high. As pointed out by Rubens, the ordinary mantle, with its approximately one per cent. of ceria, is practically black for the blue end of the spectrum. This blackness is identical with the yellow coloration on heating, which has already been mentioned. When hot, as shown by the emissive power curves, the ordinary mantle, which is white when cold, becomes deep brown in color. This coloration is due to the occurrence in the hot ceria of an absorption band whose long wave end is comparatively abrupt, and which is almost completely developed with only a small amount of ceria present. This is shown in another way by the ratio of hot to cold reflecting power through the spectrum for a 1 per cent. ceria mantle, Fig. 18 (I). Since the cold mantle is practically white, the hot mantle is thus shown to be strongly yellow.

On the addition of more ceria beyond one per cent., the absorption extends somewhat toward the infra-red, in which region a general absorption also develops. Due to this increased absorbing (emitting) power, the emission increases and the temperature falls. This fall of temperature is at once reflected in the lower emission for the short visible wave-lengths, with the resultant fall in luminosity.

The actual values attained by the emissive powers are, for the most luminous condition, less than 50 per cent., even with pure ceria, except for the visible region, and the very long wave infra-

FIG. 18.

Relationship between hot and cold reflecting power in thoria-ceria mixtures:
 I. Behavior in different parts of spectrum.
 II. Behavior of various mixture proportions in the flame and under cathode-ray bombardment.

red beyond 9μ , where saturation is again approached. There is thus a region of low emissive power centering around 4μ which, as will be seen, occurs in most of the oxides.

Behavior in Different Parts of the Flame.

The fact that ceria has a different emissive power in the oxidizing and reducing flame was noted by Féry⁸ in 1903, and he built largely upon this fact a theory that the efficiency of the mantle is to be explained by the highly emitting ceria in a reducing condition, imbedded in thoria, which is poorly emitting in the same condition. This theory is inadequate, for it does not take into account the different spectral distribution of emissive power of the two constituents, which is really the dominating factor, and, moreover, in the ordinary mantle burner the flame is *oxidizing* on the outside, not reducing. It is only when the flame is made so full as to envelop the mantle that the latter is subject to reducing conditions.

With a view to determining more specifically the change in character occurring in going from one type of flame to another, a supplementary set of spectral emission curves was made, and also some experiments on fragments of mantle heated in the interior of the flame and cooled in a reducing atmosphere.

The emission curves were made on a mantle of 80 per cent. thoria and 20 per cent. ceria composition, which exhibited the characteristic behavior excellently. Extreme conditions of the flame were taken so that the results do not form part of the same series as the curves already shown. The oxidizing and reducing flame emission curves are shown in Fig. 19 (I and II), and the corresponding emissive power distributions in Fig. 21 (III), while in Fig. 18 (I) are exhibited the changes of reflecting power in the visible region for the two kinds of heating. It is evident from these curves that not only is the emissive power in the reducing flame much higher, but it is less selective. The mantle approximates *gray* rather than brown, as is well shown by the hot and cold reflecting powers, where the very great drop in reflecting power in the blue, which is characteristic of ceria in the ordinary mantle, is greatly decreased.

This conclusion is supported by the experiments on heating a fragment of the mantle in the inner part of a Meker burner flame, which is practically free from oxygen (less than 0.1 per cent.), and removing the fragment through a quartz tube inserted in the flame, so that it cools in the products of combustion. The fragment thus treated comes out *dark gray*. Furthermore, if it is heated in hydrogen it turns *black*. In either case, upon heating in

the oxidizing flame the mantle material at once reassumes its ordinary color.

The various changes gone through by ceria on heating are probably to be ascribed to the formation of several different oxides, for whose existence there is other evidence. The ordinary is CeO_2 , the yellow formed on heating in the oxidizing flame is perhaps CeO_3 , the gray or blue⁹ formed in the reducing flame Ce_4O_7 .

FIG. 19.

Characteristics of mixtures rich in ceria in oxidizing and reducing flames:

- I. Spectral distribution of emission.
- II. Spectral distribution of emission, visible region.
- III. Spectral distribution of emissive power.

Behavior in the Cathode Discharge Tube.

A question long outstanding has been why the Welsbach mantle, and the materials composing it, behave altogether differently when heated in the flame and when heated by the bombardment of cathode rays. Campbell-Swinton,¹⁰ in 1899, performed the experiment of heating a composite "mantle" composed of sectors of pure thoria, pure ceria, and the Welsbach mixture in a cathode-ray tube. He found two striking differences between the behavior of the mantles there and in the flame. First, the 99 per cent. thoria and 1 per cent. ceria mixture gave no more light than the pure thoria. Second, while the pure thoria gave a vivid incandescence, the pure ceria gave scarcely any light; in the

flame the light given by pure thoria and pure ceria is not greatly different in intensity, although very different in color.

In order to repeat this experiment, use was made of the cathode-discharge tube already described, Fig. 2, and some four-part disk mantles of the design shown in the same figure, one of the sectors being pure thoria, one pure ceria, one 99 per cent. thoria and 1 per cent. ceria, and the fourth, 90 per cent. thoria and 10 per cent. ceria. On subjecting these to the cathode discharge the behavior described by Swinton was observed, the luminosity being greatest for the thoria, which gave a brilliant light, and decreasing according to the amount of ceria, the pure ceria giving only a dull glow. After continued bombardment the pure thoria sector was apparently unchanged, while those containing ceria became darkened to a bluish-gray. On heating in air this darkening disappeared, restoring the mantle to its original appearance. This darkening is thus ascribable to the well-known reducing action of the cathode discharge.

It was suspected that the failure of a small admixture of ceria to enhance the luminosity of the thoria was due to the failure to develop the strong visible absorption band, to which, as has been pointed out, is chiefly due the efficiency of the flame-heated mantle. In order to test this hypothesis a series of measurements were made of the ratio of hot to cold reflecting power for blue light (0.45μ), both in the cathode discharge and in the flame. The results are shown in Fig. 18 (II). It is evident at once that the great increase of absorbing power conferred by the small addition of ceria to the thoria in the flame, is largely inhibited in the cathode discharge. Whereas, the blue reflecting power for one per cent. of ceria drops to 20 per cent. of its cold value on flame heating, it only falls off a matter of ten per cent. in the discharge tube. At the same time, as was shown by the experiments on heating in the reducing flame, a reducing condition increases the general emissive power of ceria, so that the effect of ceria in reducing the mantle temperature is favored in the discharge tube. The net result of thus inhibiting the selective absorption in the blue and increasing the general absorption is to quite destroy the merits of ceria as a coloring agent for thoria. More than that, while the ceria is in its most completely radiating condition when it assumes the lowest temperature, thoria, which, according to the work of Féry, has its lowest emissive power in the reducing flame,

is probably also assuming a relatively higher temperature in the cathode discharge, whereby its luminosity is enhanced. Consequently the approximate equality of the ceria and thoria mantles in the oxidizing flame is no longer present in the cathode discharge. This behavior is not the complete explanation of this great difference in luminosity, which will be more fully treated when the question of convection and conduction losses is taken up.

Behavior in a Vacuum and in a Hydrogen-chlorine Flame.

Realization of the importance of the oxidizing condition led to trials of the effect of heating the mantle in the entire absence of oxygen. First the experiment was tried of heating ceria in a quartz tube which was connected with a pump and maintained at a high vacuum. It was thought that under these conditions the ceria might not show the characteristic yellowing. The experiment showed, however, that the usual yellowing took place.

Next a special mantle was made up divided vertically into two parts, one pure thoria, the other the regular mantle mixture. This was heated by a hydrogen flame burning in air under a bell jar, from which the air was then displaced by chlorine gas. A similar experiment was performed by Killing¹¹ to test the alternate oxidation and reduction theory of Auer, but his object was merely to determine whether the mantle became incandescent and not whether the coloring action of ceria was present. Our experiment showed clearly that the relative brilliancy of the thoria and thoria-ceria mixtures was little, if any, affected by the change from air to chlorine.

It appears from these two experiments that mere absence of oxygen is not sufficient to prevent the ceria from turning yellow and so coloring the mantle. An actual actively reducing condition, such as the cathode discharge tube, is essential. Even the reducing region of the Bunsen burner, although it causes the large drop in temperature and luminosity already noted in pure ceria, does not noticeably affect detrimentally the behavior of the regular mantle mixture. It thus appears that the absorption band in the blue region and the general absorption through the infra-red behave as though due to separate mechanisms. The latter is rather easily increased by a non-oxidizing condition; the former is only inhibited by a very strongly reducing one.

2. Thoria-uranium Oxide.

Physical Characteristics and Behavior in General.

Of all the mantle mixtures studied, those of uranium oxide with thoria show the nearest approach in efficiency to the regular Welsbach mantle. The approach is, however, only to about 50 per cent. of that efficiency. In some other respects, however, uranium oxide is even more interesting than ceria in its coloring action.

FIG. 20.

- Reflecting-power characteristics of thoria-uranium oxide mixtures:
- I. Spectral distribution, visible region.
 - II. Reflecting-power-constitution relation for 0.45μ .
 - III. Ratio of hot to cold reflecting power at 0.45μ for mixtures from 0 to 5 per cent. uranium oxide.

Uranium oxide itself is a deep brown, nearly black substance, which cannot be made up into a well-shaped mantle. As it is mixed with thoria the mixture is progressively lighter brown in color, until at about 7 per cent. uranium oxide, where it is nearly white, the mixture starts to assume a lemon-yellow color, which is at a maximum near 0.35 per cent., after which the yellow becomes paler until the white of pure thoria is reached. This series of changes is shown in the spectral reflecting power curves of Fig. 20 (I) and more clearly in the isochromatic reflecting power constitution curve of Fig. 20 (II) for 0.45μ .

A further interesting property of this lemon-yellow coloration is found on examining the relation of hot to cold reflecting power at $0.45\ \mu$ as shown in Fig. 20 (III). On applying this ratio to the cold reflecting power isochromatic, thus obtaining approximately the hot reflecting power behavior with varying concentration, it is seen that the maximum absorption is shifted to a higher percentage of uranium oxide. Thus, while the maximum coloration cold is about 0.35 per cent., it is about 0.7 per cent. hot.

FIG. 21.

Characteristics of thoria-uranium oxide mixtures:
 I. Spectral distribution of emission.
 II. Spectral distribution of emission, visible region.
 III. Emission-constitution isochromatics.
 IV. Radiant luminous efficiency-constitution relation.
 V. Temperature-constitution relation.

This absorption band has much in common with the band developed in the same region by ceria, and, like it, is responsible for the comparatively high luminous efficiency attained.

Considerable difficulty was experienced in obtaining consistent results in the visible spectrum with the uranium oxide mantles, due to the somewhat transient character of the yellow coloration. It appears either to volatilize, leaving the mantle streaked, or to be dependent on the oxidizing or reducing character of the flame at the time of extinguishing. Like the ceria coloration, it is inhibited by the reducing condition of the cathode discharge, in

which the most efficient thoria-uranium oxide mixture shows no advantage over pure thoria.

Temperature and Total Radiation.

The drop in temperature produced by adding uranium oxide to thoria is much more rapid than the drop due to ceria. It is shown for the first 5 per cent. addition in Fig. 21 (V). Already for only 5 per cent. the temperature is reduced to 1500° , where with ceria in the reducing flame the corresponding drop is only to about 1700° . The total radiation is fixed approximately, in accordance with the relationship shown in Fig. 10 (I), by the temperatures.

Radiant Luminous Efficiency.

The relationship between constitution and radiant luminous efficiency shown in Fig. 21 (IV) is unique among the mantles studied in showing two maxima. The first of these occurs at about 0.35 per cent. uranium oxide, the second at about 1 per cent. They are obviously connected, as is borne out by the spectral distribution, the first with the transient yellow coloration, the second with the steadily increasing brown coloration. Due to the latter alone, this series of mixtures would be similar to the ceria mixtures and others to be treated later. The maximum efficiency (0.00089) would be only slightly over that of a black body at the same temperature. The initial yellow coloration gives an efficiency (0.002), more than half as much again as the black body at the same temperature (lower light line), and this temperature, because of the small general emission for this concentration (0.35 per cent.), is quite high.

Spectral Emission and Emissive Power Distribution.

These are shown in Figs. 21 (I, II, and III) and 22 (I, II, and III), which are largely self-explanatory. The emissive power in the infra-red rises much higher than for ceria, in agreement with the temperature data, and exhibits a steady increase with concentration. In the visible region the emissive power and the emission show the characteristic maximum at 0.35–0.50 per cent., the emissive power continuing to rise after passing through the minimum at 0.8 per cent., the emission rising slightly, but then falling off because of the drop in temperature. The very irregular character of the isochromatics (III) is probably in part due to

the difficulties of exact measurement introduced by volatilization, already noted.

3. Thoria-manganese Oxide.

Physical Characteristics and Behavior in General.

Manganese oxide behaves much as uranium would were it not for the latter's anomalous behavior in the region where it shows

FIG. 22.

the lemon-yellow coloration. Manganese oxide is dark brown, nearly black in color, and its mixtures with thoria show a regular progression of color down to the white of the latter.

Perhaps the feature of most interest displayed by manganese is its tendency to decolorize on heating, thus being opposite in

behavior to ceria, although the amount of the effect is much less. It is exhibited by the ratio of hot to cold reflecting power, which is 1.35 for wave-length 0.55μ for 100 per cent. manganese oxide. It is also shown in a very striking manner by moving a thoriamanganese oxide mantle from the outside to the inside of the Bunsen flame. On the outer edge of the flame the mantle is dull; inside it glows brilliantly, thus being exactly opposite in behavior

FIG. 23.

to ceria. The visible decolorizing is apparently produced by the oxidizing flame. It is possible, also, that a decrease of infra-red emissive power is brought about by the reducing flame.

Temperature and Efficiency Characteristics.

The variation of temperature with concentration, Fig. 23 (V), is of the same character as with uranium and of nearly the same magnitude.

The radiant luminous efficiency, as shown in Fig. 23 (IV), goes through the maximum characteristic of mixtures with thoriamanganese oxide.

of substances of relatively high visible emissive power. The highest efficiency attained 0.0009, for 0.25 per cent. is, however, only slightly above the black body at the same temperature (light line), and, while for higher concentrations the advantage over the black body is greater, the decreased temperature reduces the efficiency to insignificant values.

Spectral Emission and Emissive Power Distribution.

These are exhibited in Fig. 24, which is self-explanatory. As in the case of uranium, a high visible emissive power, comparable

FIG. 24.

Emissive-power characteristics of thorium-manganese oxide mixtures:
 I. Spectral distribution of emissive power.
 II. Spectral distribution of emissive power, visible region.
 III. Constitution-emissive-power isochromatics.

to that of ceria, is of small value for light-production because of the large amount of general infra-red absorption. The isochromatics show clearly the whitening which sets in in the visible region with higher concentrations of manganese.

4. Thorium-nickel Oxide.

Nickel belongs with a group, which includes cobalt, chromium, and vanadium, upon which very little time was spent, because of

the small interest from the standpoint of light-production. In each case the total emissive power is large, resulting in a rapid drop of temperature for quite low admixtures with thorium. They exhibit the characteristic increase of luminous efficiency over thorium for small admixtures, but this increase is not in any way comparable with that shown by uranium or cerium.

The spectral emission and emissive power curves for 1 per cent. and 5 per cent. nickel are shown in Fig. 25 (I and II). The corresponding temperatures are 1250° and 1360° K. (IV). Nickel oxide is, of all substances measured, the blackest, having

for 5 per cent. already a higher emissive power than pure cerium or uranium oxide. The blackness of the visible region of the thorium-nickel mixture is increased by the reducing cathode-discharge bombardment.

5. Thorium-lanthanum Oxide.

Lanthanum is of peculiar interest because, while a single oxide, it exhibits the spectral distribution of emissive power and the changes between the hot and cold states characteristic of the thorium-ceria mixture, not, however, to nearly so useful an extent. When cold, lanthana is, if dry, white. On standing it takes up water, swells, and assumes a brownish tinge. It is too fragile, after thus standing, for use as a mantle. The majority of the

measurements made were confined to mixtures with thoria up to 50 per cent., because the higher percentages of lanthana would not hold together long enough.

Temperature Characteristics.

In Fig. 26 (V) is shown the temperature-concentration relation. It will be noted that the temperature is pulled down very much less rapidly by lanthanum than by any of the oxides thus far studied. The drop in temperature is, however, quite rapid for the first 5 per cent. addition.

FIG. 26.

Radiant Luminous Efficiency.

The variation of radiant luminous efficiency with concentration is shown in Fig. 26 (IV). We have here the usual optimum occurring, but, unlike all the others so far, the optimum is not for very small percentages, but near the 50 per cent. point. The reason for this is evident when it is noted that the efficiency of pure lanthana is more than twice that of pure thoria, whereas in all previous cases the efficiency of the pure colorant has been below that of thoria, and the temperatures they assume very much lower than that assumed by lanthana. The behavior of lanthanum oxide is easiest described by noting that it might be replaced by a definite mixture similar in many respects to a thoria-ceria one,

containing about twice as much colorant as enough to give the maximum efficiency.

Spectral Emission and Emissive Power Distribution.

These are shown for 2, 20, and 50 per cent. lanthana in Fig. 26 (I, II, and III) and Fig. 27 (I, II, and III). The noteworthy similarity with the thoria-ceria mixture is evident. From the

FIG. 27.

Emissive-power characteristics of thoria-lanthanum oxide mixtures:
 I. Spectral distribution of emissive power.
 II. Spectral distribution of emissive power, visible region.
 III. Constitution-emissive-power isochromatics.

emissive power curve it is seen that when hot this substance develops an absorption band in the visible region, just as does the ordinary Welsbach mantle. This band and the yellowing due to standing in the atmosphere are undoubtedly allied. Unlike ceria, however, this visible absorption band only assumes considerable values for high concentrations of lanthana, with which is associated sufficient general infra-red emission to pull the temperature down below the useful point.

6. Thoria-praseodymium Oxide.

Mixtures of thoria with neodymium and praseodymium present a number of interesting phenomena, which, properly interpreted, must undoubtedly throw some light on the chemical relationship of the two and on the nature of the mechanism which produces their peculiar spectra. For reasons which will appear, they must be considered in the relation to each other, and, for simplicity's sake, the first one to describe is praseodymium.

General Physical Characteristics and Behavior.

Praseodymium oxide (Pr_2O_3) is dark brown or black. With thoria it gives dark brown mixtures, even when present only to

FIG. 28.

Characteristics of thoria-praseodymium oxide mixtures:
 I. Spectral distribution of emission.
 II. Spectral distribution of emission, visible region.
 III. Constitution-emission isochromatics.
 IV. Radiant luminous efficiency constitution relation.
 V. Constitution-temperature relation.

the amount of a fraction of one per cent. This brown is, however, a function of the state of oxidation. When heated anywhere, except at the extreme outer edge of the flame (where it is most brilliant), it whitens, as is shown clearly by the ratio of hot to cold reflection power in Fig. 29 (IV) for wave-length 0.45μ . It appears from this that for one per cent. of praseodymium, where the effect is a maximum, the increase in reflecting power on heating is no less than six times. This phenomenon is again demonstrated by withdrawing a mantle fragment from the in-

terior of the reducing flame, from which it emerges white; by subjecting it to the cathode discharge, with the same effect, and finally by heating the oxide in a stream of hydrogen. This latter experiment is commonly reported as furnishing a *green* lower oxide. With the praseodymium used for this work, which was obtained from 4380 fractional crystallizations and used by Baxter in his atomic weight determination, the product is *white*.

FIG. 29.

- Emissive-power characteristics of Thoria-praseodymium oxide mixtures:
- I. Spectral distribution of emissive power.
 - II. Spectral distribution of emissive power, visible region.
 - III. Constitution-emission isochromatics.
 - IV. Ratio of hot to cold reflecting powers for wave-length 0.45μ for various proportions of praseodymium.

Temperature and Luminous Efficiency.

The temperature composition plot of Fig. 28* (V) shows that praseodymium pulls down the mantle temperatures about as does ceria in its condition of maximum emissive power.

From the plot of radiant luminous efficiency against composition (IV) it is seen that the maximum efficiency never attains that of a black body at the same temperature.

Spectral Emission and Emissive Power Distribution.

These are shown in Fig. 28 (I, II, and III) and Fig. 29 (I, II, and III). The most striking point is the low visible

emissive power, due to the whitening process, by reason of which is the failure, just noted, to attain a reasonable efficiency.

7. *Thoria-neodymium Oxide.*

Physical Characteristics and Behavior in General.

Neodymium is of extreme interest in optics from the fact that the absorption and emission bands of practically all its compounds are of extreme narrowness and sharpness. In the vast majority of solids, particularly the oxides, the absorption bands are wide and diffuse, with no well-marked beginning or end in the spectrum. This is true, as has just been seen, even with praseodymium, which is closely allied with neodymium. From the standpoint of light-production, neodymium oxide is of exceptional interest because its sharply defined absorption bands exemplify the kind of absorption which would be postulated for an ideal coloring material to be added to thoria in place of the somewhat extended absorption of the ceria band, narrow as that is.

Pure neodymium oxide, when freshly reduced, has a pinkish-white color, due to the presence of strong, narrow absorption bands in the green and yellow-green. On long heating this pink changes to a blue tinge, and the absorption band in the yellow-green spreads out into a multiple band in the yellow. Still another form, light brown in color, may be formed under certain conditions. Thus, if the pinkish oxide is gently heated in a quartz tube, through which air may pass, it turns to brown. A pure neodymium oxide mantle which had been laid aside for several months was found to have turned to this brown form, to return to grayish or bluish white, on igniting. The brown oxide formed by gentle heating in the manner described is reduced to the blue-gray form by contact with the reducing flame. The spectrum of this brown form appears continuous in a small spectroscope.

This brown coloration has been variously ascribed to impurities (*e.g.*, praseodymium) and to the formation of a hydrated oxide. The latter appears the more likely from our observation. At any rate, the occasional brown appearance of the pure oxide plays no apparent part in its radiating characteristics, as it is so entirely destroyed by the kind of heating a mantle gets in a flame. It is chiefly dwelt on here because of its possible connection with the extraordinary color phenomena exhibited by the thoria-neodymium mixtures, to be described next.

When neodymium oxide, which is only slightly off white, is mixed with thorium oxide, which is pure white, all the mixtures except those very close to the extremes of the series are *deep brown* in color, appearing, and, as will be seen, behaving, very much like the mixtures of thoria with praseodymium. In this brown mixture the typical banded spectrum of the neodymium disappears.

FIG. 30.

THORIA-NEODYMIUM OXIDE.

Reflecting-power characteristics of thoria-neodymium oxide mixtures:

- I. Spectral distribution of reflecting power (in terms of MgO=unity).
- II. Reflecting-power-constitution isochromatic for 0.55μ .
- III. Ratio of hot to cold reflecting power through the spectrum for a 5 per cent. neodymium oxide 95 per cent. thoria mixture.

This phenomenon is illustrated in detail by the spectral reflecting power curves (in terms of MgO as unity) of Fig. 30 (I). It will be noted that the banded spectrum of the neodymium is, as it were, buried by the general absorption which gives the brown color. Fig. 30 (II), showing the variation of reflecting power with composition at wave-length 0.55μ , exhibits the behavior even more graphically. It is remarkable that the addition of five per

cent. of white thoria to 95 per cent. of nearly white neodymium oxide should result in a deep brown substance.

On heating these brown mixture mantles in the flame they are unchanged, judged by their appearance upon cooling, thus differing from the brown color sometimes shown by pure neodymium oxide. White hot, however, our measurements show that the brown coloration quite disappears. This is shown in one way by the ratio of hot to cold reflecting power through the spectrum for

FIG. 31.

Characteristics of thoria-neodymium oxide mixtures:

- I. Spectral distribution of emission.
- II. Spectral distribution of emission, short-wave region.
- III. Constitution-emission isochromatics.
- IV. Radiant luminous efficiency-constitution relation.
- V. Constitution-temperature relation.

the 5 per cent. neodymium mixture, Fig. 30 (III). This ratio is obviously nearly complementary to the cold reflecting power, showing the elimination, while hot, of the special brown color. The spectral distribution curves show this quite clearly to be the case.

On heating in the cathode discharge, the brown mixtures behave just as the praseodymium mixtures; that is, they turn white, leaving the neodymium bands, and on heating in the air the brown color returns. Similarly, on heating inside the Bunsen

flame and withdrawing, the brown color is destroyed, until reheating is done to the oxidizing flame.

Temperature and Radiant Luminous Efficiency.

These are exhibited in Fig. 31 (IV and V). The temperature drop is not excessive, being much less than for ceria. The radiant luminous efficiency rises to nearly double that of the black body at the same temperature, and as in the case of lanthanum, though

FIG. 32.

not so conspicuously so, the maximum occurs for a fairly high percentage of neodymium admixture; namely 5 per cent., when the efficiency is 0.0013.

Spectral Distribution of Emission and Emissive Power.

These are shown in Fig. 31 (I, II, and III) and Fig. 32 (I, II, and III). The striking characteristics of these are, first, the narrow emission bands shown not only in the visible spectrum, but in the infra-red; and, second, the banded character in the visible spectrum, and the regular progression, from low to high neodymium percentages, of the emissive power in the visible

region. This latter clearly shows the destruction of the brown coloration in the hot mantle, in which the various mixtures exhibit intermediate properties between those of the ends of the series.

The emission bands peculiar to neodymium oxide have their maxima, as determined from the emission curves, at $0.54\ \mu$, $0.612\ \mu$, $0.675\ \mu$, $0.92\ \mu$, $1.12\ \mu$, $1.75\ \mu$, $2.2\ \mu$, $2.42\ \mu$, $5.25\ \mu$.

Behavior in Different Kinds of Flames.

The whitening effect of the ordinary flame and the reducing flame have already been noted. An experiment connected with the same phenomenon is illustrated by Fig. 33 (II), in which,

FIG. 33.

Characteristics of neodymium oxide mixtures with different flame adjustments:

- I. Spectral distribution of emission.
II. Spectral distribution of emission, visible region.

using a 75 per cent. Nd, 25 per cent. Th mantle, the flame was turned quite low, with the result (unbanded curve) that *the characteristic visible emission bands disappeared*. The emission spectrum is, in fact, of the character to be expected from a brown radiator.

This unbanded spectrum was no longer possible to produce after the mantle had been burned for some time, as is indicated by the second set of curves shown, marked "High and low adjustment." The infra-red measurements made after the mantle had lost its original characteristics to some extent are shown in Fig. 33 (I), in which, nevertheless, a decrease in the near infra-red banded structure is still apparent.

Similarity of Neodymium and Praseodymium in Mixtures with Thoria.

From the data shown it is to be seen that the mixtures of neodymium and praseodymium with thoria have many points of similarity. They show the same color and kind of spectrum. They both whiten in reducing conditions. They might, in short, be mistaken for each other, especially in the lower percentages where the whitened neodymium mixtures show the neodymium bands only very slightly.

The suggested explanations noted above for the brown coloration of neodymium oxide—namely, that it contains praseodymium as an impurity, or is hydrated—appear inadequate for the present case. The amount of praseodymium present in the neodymium oxide used is believed to be less than 1 per cent., so that the 5 per cent. mixture, which is deeply colored, would have less than 1/20 per cent., and this quantity of the pure praseodymium scarcely colors the thoria at all. A coloration of neodymium oxide due to the presence of cerium has been previously noted by other workers, but was explained as actually due to praseodymium, for which the cerium was acting as an oxygen carrier. It appears from this present work that the occurrence of the brown mixture, with its continuous spectrum, is less likely to be due to impurity, particularly praseodymium, than to an altered configuration of the atoms. Further study of this point would be of great interest as possibly throwing light on the structure of the atoms of the neodymium compounds.

One observation made in obtaining the praseodymium mixture curves may be recorded, although it has not been repeated; namely, the appearance under one condition of adjustment of the shorter infra-red bands characteristic of neodymium.

8. Thoria-erbium Oxide.

Complete measurements were made on only one mixture of erbium and thorium—namely, 33 per cent. erbium oxide—tests on a small sample of oxide having indicated that only in large percentages would the visible absorption bands of erbium oxide be broad enough to be of any promise for coloring.

Temperature measurements were made on this mantle and on a series of regular thoria-ceria mantles, to which had been added 1, 2, and 5 per cent. of erbium oxide in an experiment to see if

the visible erbium band would add anything of value to the ceria band. These temperature points are shown in Fig. 34 (III). The general emissive power of erbia is low, resulting in a low temperature drop. The net result of adding erbia to the regular mantle, in spite of its small effect on the temperature, is a reduction in efficiency.

Spectral distribution curves of emission and emissive power are shown in Fig. 34 (I, II, and III). The narrow emission bands, similar in character to those of neodymium, are too narrow in the visible spectrum to aid substantially in light-production, and are offset by similar bands in the near infra-red.

FIG. 34.

- Characteristics of thoria-erbium oxide mixtures:
 I. Spectral distribution of emission, 33 per cent. erbia; 67 per cent. thoria.
 II. Same, visible region.
 III. Constitution-temperature relation.
 IV. Spectral distribution of emissive power.

9. Other Oxides.

Besides the oxides for which data have been given, a number of others were investigated, which, for one reason or another, it did not appear profitable to attempt to measure in mantle form. Among them may be mentioned Barium, Cadmium, Calcium, Iron, Molybdenum, Strontium, Titanium, Tungsten, and Zinc, which exhibited volatilization or other defects.

Mention should be made also of platinum, which, applied in the form of a spray of platinic chloride, greatly increases the efficiency of the thoria mantle, but volatilizes so rapidly as to defy measurement and use.

10. General Summary on Oxide Mixtures.

It is shown by the data on the various mixtures of coloring oxides with thoria that their behavior is in general the same, differing, however, greatly in degree. In all cases an optimum mixture proportion is found. The value of the luminous efficiency

at the optimum is greatest for ceria, below which come uranium oxide and neodymium oxide, both exhibiting an efficiency notably above the black body: The other oxides have at their optimum mixtures efficiencies too low to be of much interest.

The comparatively high efficiency of both the cerium and uranium oxides is due to the presence of a strong absorption band in the blue end of the visible spectrum. In the case of ceria this band is present only when the oxide is hot; in the uranium oxide it is present also in the cold condition. Other oxides—namely, manganese and praseodymium—bleach when hot, thereby partly losing their visible absorption bands, with consequent low efficiency.

It appears to be a general characteristic of all the coloring materials to rise in emissive power in the visible spectrum, indicating that the absorption bands, which give visible coloration, have their centres in the ultra-violet region. This is in agreement with their integral visual color, which is never blue, but always yellow or brown. To this is to be added the very general relative transparency in the infra-red from $1\ \mu$ to $5\ \mu$. Both of these characteristics may be to some extent due to the mechanical structure of the mantle. Thus a roughened transparent substance, such as a piece of ground rock-salt, ceases to scatter light when the wave-length becomes long compared to the magnitude of the separate surfaces constituting the roughening; that is, in the infra-red. Also, the absorbing, or scattering, effect of small particles, in which state the coloring material may be present, decreases with increasing wave-length.

One of the most interesting facts brought out by the data is that the color characteristics of mixtures are not always simply additive. This is exemplified by the extraordinary behavior of the neodymium mixtures. In their case, however, the new coloration due to the mixture is present only in the cold condition. If it were known how such colors, different from those of the constituents, originated, a new field for the search for coloring materials might be opened.

IX. MISCELLANEOUS DATA.

Effect of Variation in Weight on Mantle Temperature.

As has been mentioned before, it was not feasible to determine for each mantle material investigated the weight to give the best

compromise between luminous efficiency and mechanical properties. It is therefore of considerable importance to know how the temperature of a representative mantle varies with the weight. For this purpose a series of pure thoria mantles was made up, varying from 0.65 to 1.4 units in weight, and temperature measurements were made on them by the thermocouple method.

These measurements showed a nearly rectilinear relation between weight and temperature over this range, from 1930° for the lightest to 1860° for the heaviest mantle. Taking this as representative, it is evident that no important alteration in the relative standing of the various "bases" could be brought about by practical variations in their weight in mantle form. The nearest "base" to thoria—namely, magnesite (1840°)—might by a very considerable reduction in weight approximate the ordinary weight thoria mantle. It is, however, so inferior to the latter in mechanical strength and durability as to make this probability of small promise.

X. GENERAL DISCUSSION OF MANTLE EFFICIENCY AND ITS LIMITATIONS.

1. *Limitation to Radiant Luminous Efficiency Set by Attainable Temperature.*

Of the two variables at our disposal in selective temperature radiation—temperature, and the composition of the radiator—the first meets with a definite limitation in the case of the gas mantle in the temperature of the flame used for heating. With ordinary illuminating gas under the pressures common in commercial practice the attainable flame temperature is in the neighborhood of 2100° K. From the standpoint of light-production, this temperature is excessively low, being approximately that of the carbon filament, and lying some hundreds of degrees lower than the operating temperatures of the tungsten filament incandescent lamps. The radiant luminous efficiency of the black body at 2100° K. is about $\frac{1}{2}$ per cent.; consequently the task of attaining an efficiency of only a few per cent. calls for a radiator of most pronouncedly selective character, even assuming that the flame temperature were taken by the radiator, which would be the case only if the latter's emissive power were of the order of 1 per cent. or less. With higher emissive powers the temperature assumed is, as has been seen, reduced, and this means a rapid loss of efficiency.

In order to learn approximately what improvement in effi-

ciency might be expected if the regular mantle could be operated at higher temperature, a series of measurements were made on a mantle heated in a flame fed with various amounts of oxygen. Radiant luminous efficiencies were measured against optically read temperatures. The results are plotted in Fig. 13 (II), from which it appears that the efficiency of the radiation increases by about three times as the temperature rises from 1900° (regular mantle temperature) to 2100° . This rate of increase is approximately that of the black body, and if continued at the same rate would mean the attainment of an efficiency some twenty times greater at 3000° , which is somewhere near the temperature of operation of the nitrogen-filled tungsten lamp. Actually the rate of increase of efficiency could be made more rapid, because a progressively larger amount of ceria could be added to advantage at the higher temperatures. Such an efficiency (9 per cent.) is far above any present incandescent illuminant, and shows clearly that the actual low efficiency of the mantle is not so much the fault of its radiating properties as of the temperature to which it is limited. (This speculation says nothing with regard to the effect on the various heat losses were such a temperature attained, which will be treated separately below.)

2. *Limitations to Radiant Luminous Efficiency Set by the Temperatures Which the Mantle Materials will Stand.*

Aside from the question of means for attaining higher efficiency by higher temperatures, a vital matter to be considered is the effect of higher temperatures on the mantle materials.

The melting-point of thoria is given by Ruff¹² as 2440° C. (2713° K.), and that of ceria as 1950° C. (2223° K.). The former temperature is, of course, the upper limit of operation of a thoria base mantle, the lower that of a mantle containing ceria. There is good evidence, however, that ceria begins to volatilize at the ordinary mantle operating temperature. White and Mueller¹³ have made observations on various mantles before and after burning for extended periods, and demonstrated the loss of ceria both by the variation in efficiency and by analysis. The increasing rate of candle-power depreciation with high-pressure burners is in line with their findings.

Closely allied to this question of melting and volatilization points is that of the physical strength of the mantle. This must

be sufficient to give a useful life when subject to the average shocks of operation. The lighter the structure can be the higher the temperature it can take, as shown by the data on the thorium mantles of various weights, and the exact compromise between durability and efficiency must be determined from practical considerations.

3. *Radiant Luminous Efficiencies Theoretically Attainable with the Bunsen Flame and Thorium Base.*

The attainment of the maximum possible efficiency, and the high efficiencies which have been suggested as possible from the materials of the present Welsbach mantle, would demand a freedom in the choice of radiating materials on the one hand, or of temperatures on the other, which we are far from realizing. It therefore becomes of interest, having established the limits of temperature at our disposal, and the characteristics of the radiator of lowest emissive power at our disposal (thorium), to investigate what efficiencies should be theoretically possible under the limitations thus set. All of the information necessary for such calculations is now at our disposal.

Let us first consider the possibilities of the Bunsen flame as a "base" for carrying a layer of selective radiator. We shall assume that its temperature is 1800°C. (2073°K.), and for its total emissive power we shall take the values resulting from using the actual radiation as measured in this investigation, which is 0.0116. We may further assume, without material inaccuracy, that the flame gives no appreciable light.

In Fig. 35 is plotted (BB) the spectral emission curve of the black body at 2073°K. for the visible region, and (L) the luminosity curve for the same black body. The ratio of the area of this luminosity curve to the area of the complete emission curve is the luminous efficiency of the black-body radiation at this temperature, and has the value 0.0032. Now, with this piece of information at our disposal, it is at once possible to calculate the contribution to the total radiation and to the total light of any emissive power in any part of the visible spectrum. The process is shown graphically in the figure. We first assume that to the colorless Bunsen flame is added a narrow zone of unit emissive power at the wave-length of maximum luminous efficiency. For ease of calculation we may take this band fairly wide, say $0.05\ \mu$.

Call this zone I. The addition to the total radiant energy is the area of this zone lying under curve BB; the addition to the luminous energy is the area lying under the curve L, each, of

FIG. 35.

Calculation of possible radiant luminous efficiencies using the Bunsen flame (full lines) and thoria (dashed lines) as bases.

course, being expressed in the unit fixed by the value of the area of curve L, above derived. Thus for zone I the area under BB, in terms of the area $L = 0.0032$, is 0.00175; the area under L is

0.00107. From this we get that the radiant luminous efficiency of the Bunsen flame + zone I of unit emissive power—*i.e.*, the ratio of the luminous to the total energy—is

$$\frac{.00107}{.0116 + .00175} = .08$$

Adding by this same process successive zones on each side of the original one of lower and lower luminous efficiency, we obtain for the luminous efficiencies as follows:

Bunsen flame + Zone I	0.084
Bunsen flame + Zone I + Zone II	.159
Bunsen flame + Zone I + Zone II + Zone III	.169
Bunsen flame + Zone I + Zone II + Zone III + Zone IV .	.166

Beyond this point the added zones lying largely or wholly in the infra-red or ultra-violet contribute to the total energy and not to the luminous energy, and reduce the efficiency, which goes through a maximum at approximately 17 per cent.

This efficiency is subject to a certain reduction, due to the fact that the total radiation is approximately doubled by this additional emissive power, and such an increase, as we have seen, reduces the temperature of the radiator. From the experimental curve of Fig. 10 (I) we may estimate that the temperature reduction would be to about 2000° K. Assuming that the resultant drop in efficiency is approximately that which a black body would suffer by such a lowering of temperature, we make a deduction of 20 per cent., leaving an efficiency of about 13 per cent.

It is obvious that this calculation, to be highly accurate, should be carried through by quite small steps, and the change of temperature introduced at each step, but the figure obtained by the rougher method here used is substantially accurate—certainly sufficiently so for our present purposes.

It next becomes of interest to study by the same method to what efficiency we are restricted if no better base than thoria is found, assuming the possibility of adding a colorant of the ideal character represented by the zone just assumed added to the Bunsen flame. We may take, for the temperature assumed in the flame by the thoria base, 1930° K.; for its emissive power, 0.043; for the efficiency of the black body at this temperature, 0.0018, the light given by the thoria being small enough to be negligible. Proceeding as before, we obtain for

Thoria base + Zone I	0.0135
Thoria base + Zone I + Zone II	.029
Thoria base + Zone I + Zone II + Zone III	.0296
Thoria base + Zone I + Zone II + Zone III + Zone IV	.034
Thoria base + Zone I + Zone II + Zone III + Zone IV + Zone V ..	.032

As before, this efficiency must be corrected, owing to the temperature reduction caused by the radiation increasing from 0.043 to about 0.05 that of the black body at 1930°. Judging by the regular thoria-ceria mantle, this reduction would probably not amount to more than 30°, resulting in about 15 per cent. loss of efficiency, leaving a net possible radiant luminous efficiency of 0.029. This is approximately *three times* the radiant luminous efficiency given by ceria as a colorant (making the comparison with the efficiency attained in the brightest part of the mantle, where alone the assumed temperature applies).

A point of considerable interest which comes out of this study is that the maximum efficiencies thus calculated are obtained with very nearly the complete visible spectrum endowed with full emissive power. If the base were absolutely transparent and non-emissive, the most efficient coloring medium would be one with emissive power restricted to the middle, most efficient part of the spectrum; that is, one giving a yellow-green light. With the presence, however, of invisible emission in the base, a considerable quantity of visible radiation may be added, even though not all of good efficiency, before the increment to the total radiation, which is the denominator of the efficiency fraction, begins to increase at the same rate as the visible part.

It appears, from this calculation, that by using the present thoria base, without any increase of flame temperature, a very substantial increase of luminous efficiency could be obtained, provided a coloring material of the proper characteristics were available. The desired colorant would differ from ceria in two respects: First, it would add nothing to the radiation in the long wave-region near 2μ ; and, second, the absorption band which is responsible for the visible emission would be sharply defined on the red side, more like the bands of neodymium than the gentle slope of the ceria band. Of these two differences, the second would be of the greater importance, for, with everything else left the same in the ordinary mantle, any increase in the emissive

power near 0.6μ (which is only about 20 per cent.) at the expense of the emissive power at the red end of the visible spectrum and near infra-red would appear directly in the efficiency.

4. *Heat Losses in the Burner and Mantle-lighting Unit.* *Hydraulic Analogy.*

Attention has been directed chiefly in this investigation to the study of the radiating properties of various materials, and the information desired has been the luminous efficiency of their radiation. The methods of study employed give, however, information which is of interest and value on the sources of inefficiency of the whole mantle-burner combination.

Thus, as has been pointed out elsewhere, the ratio of the total luminous efficiency to the radiant luminous efficiency gives the radiational efficiency, or efficiency of transformation of the applied energy into the radiant form. The total luminous efficiency obtained from the lumens per watt rating and the mechanical equivalent of light is 0.0019. Dividing this by the radiant luminous efficiency (as obtained in this work for the horizontal direction) gives 0.44, or an efficiency of transformation of applied energy into radiant energy of less than one-half. Using an earlier figure, obtained by Karrer for the mantle with a glass chimney—namely, 0.019—this efficiency drops to about one-sixth. Without radiant luminous efficiency figures for the whole radiation (instead of in one direction only) it is not possible to calculate the radiational efficiency accurately in this way, but it is clearly quite low. A more accurate method of calculating the losses, which are obviously those due to convection and conduction, is obtained by making a heat balance for the mantle and burner. If we assume that the products of combustion leave the mantle at the temperature of the latter, we can, by knowing the specific heat of these products and their amount, calculate the amount of energy carried away by them, thus getting the convection losses, which are probably the greater portion of the losses.

The result of carrying through these calculations for a mantle at several different temperatures is shown in Fig. 9 (III). A gas of 630 B.t.u. per cubic feet was assumed, and the specific heats in B.t.u. per cubic foot of gas consumed per degree centigrade at various temperatures were plotted from standard tables. The cal-

culution then consisted in comparing the ratio of this specific heat to the initial (630).

It appears, from this figure, that the energy loss by convection is, for the ordinary mantle at about 1900° K., close to 75 per cent. Furthermore, this loss is different at different temperatures, decreasing with lower temperatures, being only about 45 per cent. for the ceria mantle temperature (1350°). Hence any increase in efficiency sought by increasing mantle temperature is, other conditions being unchanged, offset in large degree by the increase in convection losses.

The accuracy of this curve (and the validity of the assumption that the convection losses are practically the total losses) is indicated by the experimental points (circles) obtained by Kingsbury during an earlier study of radiant heaters by a calorimetric method. This decrease of radiation with increasing temperature is in entire accord with the relationship between temperature and total radiation found in connection with the measurement of temperature by total radiation.

It is evident, from a study of the figures used in the calculation, that a large part of the convection loss is due to the volume of inert nitrogen carried through the flame. The effect of this is shown graphically by the additional dashed curve of Fig. 9 (III) calculated for the condition that combustion takes place in oxygen instead of air. The losses are less than half as great, but increase with increasing temperature as with air.

The whole behavior of the burner and mantle may be represented by an extension of the hydraulic analogy suggested by Wood¹⁴ for the mantle alone.

We can imagine the mantle to be represented by a vertical cylindrical tank into which water is flowing at a constant rate from a tap (Fig. 36). The wall of the tank is to be imagined as perforated by holes of various sizes. The water which squirts out through these holes is the radiation, and the various sizes of holes represent various wave-lengths. If the smaller holes are more numerous at the top of the tank, then the higher the water rises the more will squirt out through the smaller holes, thus copying the behavior of a material radiator, water *height* being taken to represent *temperature*.

If now we take a tank containing many holes, the water will

not rise very high, and, conversely, in one with only very few holes the water will rise higher, thus copying the behavior of mantles of high and low emissive powers, in so far as their temperature characteristics are concerned. If the holes are all made small, only squirts of small size will be present, and the water will rise higher than if holes of all sizes are present, thus copying the characteristics of a selective radiator like the mantle.

In order for this tank to represent the behavior of the mantle with respect to the amount of radiation, it is only necessary to imagine a vertical seam of the tank to have been left unsoldered,

FIG. 36.

Hydraulic analogy of mantle and burner: T_m = Mantle temperature. T_f = Flame temperature.

so that a bad leak is present, to represent the convection and conduction losses. The higher the water rises, as when the radiating holes are made few in number, the more is lost through the leaky seam, and so the less is "radiated" through the holes. Obviously, with a constant rate of supply the advantage of increased "temperature" is being more and more offset by the leakage.

To go back to the actual mantle, it appears that by eliminating the convection loss the temperature attainable and its availability for producing radiation would be much increased. This is what occurs when the mantle is heated *in vacuo*. If, for instance, a ceria mantle and a thoria mantle are receiving energy at the same rate from the cathode stream, the ceria mantle saves through

elimination of convection losses and diverts to radiation about 80 per cent. more than it does of the same energy supplied by the flame; the thoria mantle, on the other hand, retains for radiating purposes *four times* what it does when heated by the flame. The effect of this on the temperature attained could be found only by studying the relation between total radiation and temperature in the mantle materials. A black body radiating n times the energy of the same body at the temperature T must have the temperature

$$\sqrt[4]{nT}$$

For 80 and 400 per cent. the increase in temperature would be approximately 15 and 40 per cent. respectively. The latter increase on 1900° would correspond to an enormously greater increase in luminous radiation than the former on the lower temperature of 1350° .

It has already been shown how the failure of ceria to color the mantle, in the cathode discharge, explains the lack of superiority of the ceria-thoria mixture over pure thoria under those conditions. The large reduction in convection losses in the vacuum tube explains why pure thoria should be so overwhelmingly superior to pure ceria in the cathode discharge, although nearly alike in the flame, thus giving a complete explanation of the differences in behavior, which have been a long-standing puzzle.

5. *The Total Luminous Efficiency Attainable with the Bunsen Flame as the Source of Heat.*

With the information on convection losses just obtained, it is of interest to consider again the limitations of the Bunsen flame as a source of heat for producing light. Thus far we have considered merely the *radiant* luminous efficiency attainable by adding an ideal colorant to the flame. This has been found to be approximately 13 per cent. with air, accompanying a temperature of about 2000° K. In order to get the *total* luminous efficiency of the burner and mantle, this figure must be multiplied by the radiational efficiency for 2000° K. as given in Fig. 9 (III); namely, 20 per cent. The total luminous efficiency thus derived is 2.6 per cent.

This figure represents the maximum possible efficiency attainable by heating a mantle in the customary manner by means of a

Bunsen flame. While over thirteen times that of the present mantle gas light (0.0019), it is yet very low as an absolute efficiency. It is, in fact, below the value already attained by the nitrogen-filled tungsten lamp (0.032). It must be remembered, however, in this connection, that the process of obtaining the stored energy from coal by the production of gas is much more efficient than is the process, employing boiler and engine, used for transforming the energy to electrical form. As a consequence the efficiency measured from the coal pile is not greatly different for the two kinds of light.

XI. GENERAL SUMMARY.

The investigation here described, in so far as it deals with the radiating characteristics of the incandescent mantle, constitutes chiefly an extension of the work of Rubens on the thoria-ceria mixtures, to a large family of such combinations. It exhibits the Welsbach mantle of commerce simply as one of a group of possible combinations of radiating materials, behaving according to the same general laws, but remarkable among them for the degree to which the characteristics of selective radiation are exhibited.

A more detailed study has been made than any heretofore on the behavior under various conditions of the absorption bands to which the enhanced visible radiation of the more efficient mantles are due. While no *explanation* has been found for the occurrence of the visible absorption bands of ceria and other materials—a question to be solved only by an intimate knowledge of the structure of matter—the information learned as to the conditions under which they appear and disappear has made possible a rather complete explanation of some long-standing enigmas, notably that of the different behavior of the mantle in flame and cathode-discharge heating.

Another line of investigation has here been taken up apparently for the first time in any detail; namely, that of the energy relations holding with flame heating of radiating materials. As a result of the study it has been possible to fix with some definiteness the possible attainable efficiencies of gas-light production by present methods. These, while low, are still many times any now reached.

NOTES.

- ¹ Rubens, *Annalen der Physik*, **20**, 3, p. 593 (1906).
- ² For instance, Wood's "Physical Optics" or Burgess and Le Chatellier's "High Temperature Measurement." An excellent review of mantle theories is given by Fulweiler, *Trans. I. E. S.*, iv, p. 65, 1909.
- ³ See Ives, "The Units and Nomenclature of Radiation and Illumination," *Astrophysical Journal*, January, 1917, p. 39.
- ⁴ Ives, "Establishment of Photometry on a Physical Basis," *JOURNAL OF THE FRANKLIN INSTITUTE*, October, 1915, p. 409.
- ⁵ Ives and Kingsbury, "Physical Photometry with a Thermopile Artificial Eye," *Physical Review*, November, 1915, p. 319.
- ⁶ White and Travers, *Jour. Soc. Chem. Ind.*, **15** (1902), p. 1012.
- ⁷ Langmuir, *Physical Review*, xxxiv, p. 401 (1912).
- ⁸ Féry, *Ann. de Chem. et de Phys.*, **27** (1902), p. 433.
- ⁹ See Levy, "The Rare Earths," p. 177.
- ¹⁰ Campbell-Swinton, *Proc. Roy. Soc.*, **65** (1899), p. 115.
- ¹¹ Killing, *Journ. für Gasbel.*, **50**, p. 90.
- ¹² Ruff, *Zeits. anag. Chem.*, **82**, p. 373 (1913).
- ¹³ White and Mueller, *Jour. Gas Lighting*, **83** (1903), p. 504.
- ¹⁴ Wood, *Physical Review*, xxiv, p. 437 (1907).

Manufacturing Destroyers. H. O' HIGGINS. (*The Official Facts*. Committee on Public Information, Washington, D. C., September, 1918).—It formerly took two years to build a fast destroyer. One has just been built in a little more than two months. These craft, costing two million dollars each, have the engine power of the old battleship *Maine* and the speed of a motor boat. Experience has shown that they are the most effective weapon against the submarine. At the outbreak of the war we succeeded in completing one in eight months instead of two years. Then, with the speeding up of production, another was completed in six months. Now, in the Mare Island Navy Yard, the destroyer *Ward* has been launched 17½ days after its keel was laid, and it has been completed in seventy days.

There is no magic in this enormously increased rate of production; we are now not building destroyers, we are manufacturing them. The process by which the *Ward* was manufactured is a machine process, by which we can produce at the same rate, as many destroyers as we need. The steel parts are prepared, in various plants, all over the country, in accordance with standardized plans. These parts are assembled in navy yards, put together at the docks, swung into position and riveted in place by a force of men working night and day. In other words standardized destroyers are being turned out as standard automobiles are turned out, in quantity production. The Navy Department reports that one flotilla of these destroyers, having steamed a million miles on patrol, has protected 86 convoys and 717 single vessels, and fought 81 submarines without any loss to the destroyers or to the vessels which they escorted.