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AN INVESTIGATION OF THE TRANSLUCENCY OF PORCELAINS

BY

CULLEN W. PARMELEE

AND

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BULLETIN NO. 154

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AN INVESTIGATION OF THE TRANSLUCENCY OF PORCELAINS

BY

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AN INVESTIGATION OF THE TRANSLUCENCY OF PORCELAINS

I. INTRODUCTION

1. *Object of Investigation.*—A knowledge of the nature of translucency together with a satisfactory means of control and measurement would be of value in many kinds of ceramic work. While it is true that translucency in art and table ware is valuable to the purchaser only from an aesthetic standpoint, to the manufacturer it has a practical value because it determines the price which can be obtained for his product.

The present investigation has for its purpose a study of the causes of translucency, and the development of an accurate method for the determination of absolute translucencies in porcelain bodies.

2. *Former Methods of Measurement.*—Translucency is a property of porcelains which lends itself easily to visual measurement. A trained observer can distinguish between two pieces with only small differences in translucency, by holding the fingers between a piece and a lamp, and noting the clearness of the shadow produced.

In order to get a more exact method of comparison which could be duplicated, some early workers made their specimens in the form of a wedge, and measured the thickness of the piece at the point where it became visibly translucent when illuminated by a specified source of light.[*]

Others observed the smallest mesh screen which gave a visible shadow through the piece.[†] Priest[‡] first suggested the use of a photometer for transparency measurements. He also indicated that absolute translucencies could be obtained in this way, so that any arbitrary selection of standards could be avoided. Measurements by a photometer have been made by the Bureau of Commerce,[¶] but no details are given.

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[*] Ashley, H. E., Trans. Amer. Ceram. Soc., Vol. 8, p. 147.
Ogden, L., Trans. Amer. Ceram. Soc., Vol. 13, p. 400.

[†] Weelans, C. and Ashley, H. E., Trans. Amer. Ceram. Soc., Vol. 13, p. 102.
Parmelee, C. W. and Baldwin, G. H., Trans. Amer. Ceram. Soc., Vol. 16, p. 534.
Watts, A. S., Trans. Amer. Ceram. Soc., Vol. 16, p. 215.
Linn, C. G., Jour. Amer. Ceram. Soc., Vol. 2, p. 622.

[‡] Priest, I. G., Trans. Amer. Ceram. Soc., Vol. 17, p. 150.

[¶] Pottery Industry, Bureau of Commerce, p. 193.

For obtaining relative translucency, Steger[*] has employed a Bougier portable photometer for which he claims considerable accuracy. Bleininger[†] suggested the use of the selenium cell for translucency determinations.

The photo-electric cell, which is the most accurate and sensitive selective radiometer known, was first used by Parmelee and Lowrance.[‡]

3. *Effect of Composition and Method of Preparation.*—In general the addition of flux increases translucency. Ogden, Hecht, Steger, and Purdy[¶] agree that high feldspar bodies have the highest translucency and high clay bodies the lowest. Kaolin gives better translucency than ball clay. Hope, Ashley, Ogden, and Riddle[§] have found that small additions of CaO, MgO, BaO, and ZnO give slight increases in translucency. Watts[**] found that soda feldspar gave a higher translucency than potash feldspar.

The effect of fineness of grind on the translucency of porcelains has not been directly studied. While working on the obscuring power of pigments, which is a problem entirely analogous to translucency of porcelains, Spear and Endres[††] found that when the average particle has a diameter of about one-half of a wave-length of light, the substance shows a maximum opacity.

Weelans and Ashley and Steger[‡‡] claimed that the relation between translucency and thickness is a linear one, and they concluded from this that the transmission is inversely proportional to the thickness. This could not be true because inverse proportionality is represented by a rectangular hyperbola and not by a straight line. Priest[¶¶] pointed out that the relation, after correcting for surface reflections, should be exponential.

Very little speculation has been made as to the nature of translucency. Mellor[§§] has shown the close analogy with the translucency of

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[*] Steger, W. Ber. Deutsch. Keram. Gesellschaft, Vol. 2, pp. 9, 65.

[†] Bleininger, A. V., Trans. Amer. Ceram. Soc., Vol. 15, p. 543.

[‡] Parmelee, C. W. and Lowrance, R. E., Jour. Amer. Ceram. Soc., Vol. 6, p. 630.

[¶] Ogden, *loc. cit.*
Hecht,-Ashley, H. E., Trans. Amer. Ceram. Soc., Vol. 13, p. 259.
Steger, *loc. cit.*
Purdy, R. C., Trans. Amer. Ceram. Soc., Vol. 13, p. 479.

[§] Hope, H., Trans. Amer. Ceram. Soc., Vol. 11, p. 494.
Ashley, *loc. cit.*
Ogden, L., Trans. Amer. Ceram. Soc., Vol. 7, p. 395.
Riddle, F. H., Jour. Amer. Ceram. Soc., Vol. 1, p. 620.

[**] Watts, *loc. cit.*

[††] Spear, E. B. and Endres, H. A., Ind. and Eng. Chem., Vol. 15, p. 725.

[‡‡] Weelans and Ashley, *loc. cit.*
Steger, *loc. cit.*

[¶¶] Priest, *loc. cit.*

[§§] Mellor, J. W., Clay and Pottery Industries.

oiled paper. This analogy has led many to believe that translucency cannot be obtained in a porous body.* Ganos,† however, prepared a body which showed good translucency, but was at the same time highly porous. Spear and Endres‡ have enumerated the factors responsible for extinction in pigments, namely, size of particle, indices of refraction, and absorption. The same considerations evidently apply for porcelains.

II. THEORY OF TRANSLUCENCY

4. *Definitions.*—Ordinarily the translucency of a substance is defined as the ratio of transmitted to incident light. While this definition may be sufficient for elementary purposes it is evident that to be explicit the wave-length of light should be stated. For monochromatic light of frequency ν the portion of light transmitted will be called a_ν.

For a complete study of the translucency of a body it would be necessary to determine the coefficient a_ν for all frequencies, obtaining the characteristic curve

$$a_\nu = a(\nu) \tag{1}$$

Practically, we are interested only in the total sensation produced on the eye by the transmitted light from a stated source of light. If S_ν is the sensitivity of the eye, and E_ν the energy in the light source, then the effect produced on the eye by the incident light is equal to

$$\int_0^\infty S_\nu E_\nu \, d\nu$$

The effect on the eye by the total transmitted light is equal to

$$\int_0^\infty S_\nu E_\nu a_\nu \, d\nu$$

The practical coefficient of translucency T' may therefore be defined as the ratio of these two effects

$$T' = \frac{\int_0^\infty S_\nu E_\nu a_\nu \, d\nu}{\int_0^\infty S_\nu E_\nu \, d\nu} \tag{2}$$

For purposes of comparison the type of lamp should be stated, so as to determine the function E.

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*Binns, *loc. cit.*

†Ganos, M. F., Moniteur de la Ceramique de la Verrerie, Sept., 1904.

‡Spear and Endres, *loc. cit.*

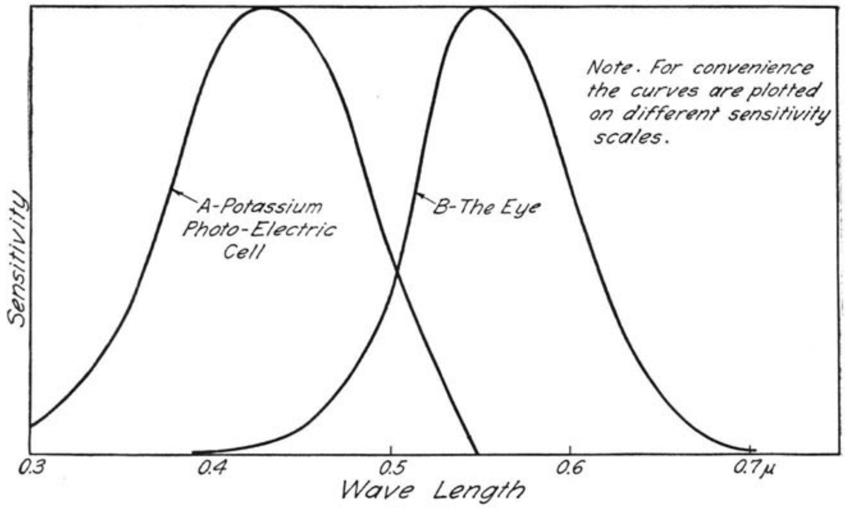

FIG. 1. SENSITIVITY CURVES FOR POTASSIUM PHOTO-ELECTRIC CELL AND FOR THE EYE

With a photometer, T' is obtained directly. In the present investigation with the photo-electric cell a slightly different value was found. The maximum sensitivity of the potassium cell occurs at a somewhat higher frequency than that of the eye (Fig. 1). If the sensitivity of the cell is S_ν', then the practical value which is obtained is

$$T = \frac{\int_0^\infty S'_\nu\, E_\nu\, a_\nu\, d\,\nu}{\int_0^\infty S'_\nu\, E_\nu\, d\,\nu} \tag{3}$$

5. *Effect of Thickness and Condition of Surface.*—The quantities a_ν, T, and T' depend on the thickness of the specimen. In a body which only absorbs radiation without reflecting or diffusing it, the amount of light transmitted would follow the exponential law

$$T = \alpha^t \tag{4}$$

where α is the coefficient of transmission for unit thickness and t is the thickness of the piece. If a portion R of the total incident light is reflected from the surface of the piece the translucency is given by the relation

$$T = \alpha^t - R\,\alpha^t = \alpha^t\,(1 - R) \tag{5}$$

If the light is diffused on traversing the specimen, additional surface and end corrections must be made. These are rather involved and would vary from piece to piece, depending on its size, shape, and diffusive power. Moreover, the pieces are probably not uniform throughout their thickness, especially near the surface where the surface tension increases the degree of vitrification.

6. *Fundamental Causes of Opacity.*—The degree of translucency of any piece must be determined by the character, amount, and distribution of the minerals which make up the body. Klein* found that porcelains consist of quartz particles imbedded in a fused matrix, composed mainly of feldspar, together with more or less granular and crystalline mullite. At low temperatures the quartz particles are well defined and there is little or no crystalline mullite. As the heat treatment increases the quartz particles gradually dissolve, the amount of fused material increases, and the granular mullite slowly changes to the crystalline variety. The opacity of porcelain and the changes in opacity with varying heat treatment and fineness must be explained on the basis of these facts.

There are only three possibilities for light incident on a specimen of porcelain, (a) reflection, (b) absorption in the piece, (c) transmission through the piece.

(a) Reflection from the specimen is due to two causes—surface reflection and internal reflection from the particles in the interior of the body. Internal reflection is, in turn, a function of the diffusive power of the medium.

(b) Absorption by any medium is dependent on two factors, the coefficient of absorption of the medium, and the distance which the ray travels in the body. This latter factor, again, is a function of the scattering power of the substance.

(c) The amount of light which is finally transmitted is the total incident number of rays minus those lost by reflection and absorption. The transmission will therefore depend on surface reflection, the coefficients of absorption of the substances in the body, and the diffusive or scattering power of the body. For a study of the causes of translucency it is therefore necessary and sufficient to determine the relation which the mineral character of porcelain bears to the surface reflection, absorption, and diffusion.

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*Klein, A. A., Technical Paper, Bureau of Standards No. 80.

7. *Surface Reflection.*—True specular surface reflection comprises only a part of the entire reflection from the piece. Since the surfaces of porcelains are generally rough, the reflection from them is highly diffuse, and consists of the sum of the light reflected from the individual surface particles. The specular reflection R from any homogeneous substance having a smooth surface can be calculated by means of Fresnel's formula

$$R = \tfrac{1}{2}\left[\frac{\sin^2(i-r)}{\sin^2(i+r)} + \frac{\tan^2(i-r)}{\tan^2(i+r)}\right] \tag{6}$$

where i is the angle of incidence and r the angle of refraction. Substitution in this formula shows that R increases with i and also with the index of refraction n, where n is equal to $\frac{\sin i}{\sin r}$. Since the average angle of incidence is increased by the roughness of the surface, the amount of surface reflection will be greater for a rough than for a smooth surface. Therefore, true surface reflection from porcelain is dependent on the roughness of the surface, and the indices of refraction of the surface minerals.

8. *Absorption.*—The constituent minerals of porcelain, namely, quartz, mullite, and glass, are all transparent, having low coefficients of absorption. The value of these coefficients is influenced by the purity of the materials used for the body. Therefore, for the best translucency the raw materials should be as free as possible from iron and other coloring oxides.

9. *Diffusion.*—This is probably the most important factor in determining the translucency of a substance, since it contributes a major portion of the reflected light, and fixes the distance which must be traveled by the rays, hence determining the total absorption. Diffusion of light inside a porcelain body can be due to five causes: (a) molecular diffusion of the pure minerals; this is so small as to be negligible in comparison with the other factors; (b) specular reflection on entering or leaving the particles of air, quartz, etc., in suspension in the body; (c) diffraction on passing through a narrow opening between particles; (d) bending of the rays by refraction on entering or leaving the particles; and (e) total reflection of the rays on entering or leaving the particles.

Consider an ideal case of a porcelain body which can be divided up so that each subdivision will consist of a single particle of air, quartz, mullite, or other insoluble mineral imbedded in a clear matrix. The total diffusive power of the body will then be the sum of the separate diffusions for each part.

The specular reflection (b) from a particle in one of these elementary volumes can be calculated by means of Fresnel's formula from the angle of incidence and the ratio of refractive indices of the matrix and particle. The rays will enter any volume in the interior of the specimen about equally from all directions, due to reflection from neighboring particles. Since the particles are oriented in any and every direction through the specimen, the effective angle of incidence will be practically constant for all bodies. The reflection will depend also on the relative volumes of the particle and matrix. Internal specular reflection for an elemental volume is therefore dependent only on the indices of refraction of the minerals and the concentration of particles in suspension.

The amount of bending of the rays by refraction (d) in the elemental volume will depend on the difference of refractive indices of matrix and particle, and also on the shape of the particle as well as the angle of incidence. As before, the angle of incidence need not be considered. In general, the amount of bending of the rays by any particle is increased by an increased irregularity of its shape. Small imperfections and roughness of surfaces are not included, since they are comparable in size to a wave-length of light, and hence will not affect the radiation. Diffusion by refraction will therefore be determined by the refractive indices of the matrix and the particle, and the shape and concentration of the particle.

Two distinct cases of total reflection (e) must be considered: first, where the particle has a higher refractive index than the matrix (quartz in glass) and second, where the reverse condition holds (air in glass). In the first case total reflection can take place only when the ray strikes the outside of the particle. Hence, the only factors affecting the reflection are the refractive indices, which determine the size of the critical angle, and the concentration of the particle.

In the second case, reflection will occur only when the ray is on the point of leaving the crystal. Here the shape of the particle must be considered as well as the refractive indices and the concentration.

Having determined the diffusive power of an elemental volume in terms of the properties and distribution of the minerals in the volume, it is now possible to add up these effects and obtain the diffusive power of the body as a whole. To summarize, the diffusion in any elementary volume is dependent on the refractive indices of the matrix and the particle, and the shape and concentration of the particle. The diffusive power of the elemental volume, which is the ratio of the amount of scattering to the total incident radiation, is independent of the size of the volume. The resultant diffusive power of a number of entirely independent volumes is therefore the same as for a single one. If the volumes are gathered together in a single body, however, their diffusions are mutually dependent, and the effective scattering is increased by the number of elemental volumes in the body. In other words, the total diffusion in a piece of porcelain will be increased by a decrease in the average size of the quartz, mullite, or air particles. This is also in accord with common experience. A piece of glass may be transparent, but by crushing and grinding it is converted to a white powder with only slight translucency.

On the other hand, when the particles become so small as to be comparable with a wave-length of light, they cease to have indices of refraction in the same sense as larger bodies. The critical point where this occurs is found by experiment to be where the diameter of the particles is about half a wave-length.* Therefore, as the size of the particle in a porcelain body decreases, the total diffusion will increase up to a certain maximum, and then decrease.

Summarizing these facts, it appears that the total diffusive power of a body is determined entirely by (a) the refractive indices of the minerals in the body, (b) the ratio of the total volume of each mineral which is held in suspension to the total volume of the body, (c) the effective shapes of the particles in suspension, and (d) the effective size of the particles.

10. *Summary of Factors Affecting Translucency.*—The three effects of surface reflection, absorption, and diffusion, as determined by the mineral character and distribution in the body, having been considered in detail, it is now possible to correlate these relations with translucency, as follows:

(a) Translucency is decreased by an increase in surface reflection, which can be accomplished by increasing the roughness of the surface, or by increasing the average index of refraction of the minerals in the body.

(b) Translucency is decreased by an increase in internal reflection, which is caused by an increase in diffusive power.

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*Spear and Endres, *loc. cit.*

(c) Translucency is decreased by an increase in the total absorption of the body, which is caused by an increase in the coefficient of absorption of the mineral constitutents, or by an increase of the distance which the light must travel in the medium, accomplished by increasing the diffusive power. The diffusive power is increased by increasing the volume of the suspended particles in a unit volume of the body; by increasing the irregularity of the shape of the particles up to a certain point; by increasing the differences of refractive indices of the matrix and the suspended particles; and by decreasing the size of the particle if its diameter is greater than half a wave-length, or increasing the size if the diameter is less than half a wave-length.

11. *Applications of Theory of Translucency.*—From these considerations many of the peculiarities of the translucency of bodies may be readily explained. The great opacifying effect of air has long been recognized. Few substances are highly translucent if their porosity is high. Powders of all kinds are opaque, even though the substance forming the powder is itself transparent. The explanation lies in the fact that air has a refractive index which differs greatly from any solid substance. There are, however, some substances which are highly porous and still show translucency, such as alundum filtering crucibles. This is probably due to the relatively large size of the individual particles and of the pores.

The high translucency of oiled paper is explained by the fact that the pores are filled with oil which has an index of refraction much nearer to that of paper than to that of air. The translucency of porcelains is due similarly to the filling of the pores by a feldspar matrix whose index of refraction is near that of quartz. Since translucency is dependent on the proportion of suspended material, it will be increased by any addition of a flux or by increasing the heat treatment. Also, increased temperatures bring about formations of crystalline mullite from the amorphous form. This change is accompanied by changes in refractive indices and fineness, with corresponding effects on translucency.

The color of the transmitted light is also of importance. The individual crystals of an alundum crucible which were examined under a microscope were found to be distinctly blue, while the light which was transmitted by the piece as a whole was yellow. In this case the explanation lies in the fact that blue light has a higher index of refraction than red, and hence it has a higher diffusion. This diffusion means that a greater distance must be traveled inside the piece, and hence greater total absorption. This effect is sufficient to off-set the natural color of the individual crystals.

TABLE No. 1

COMPOSITION OF BODIES—WEIGHT PER CENT

Nos.	Feldspar*	Flint	Clay†	Nos.	Feldspar*	Flint	Clay†
1– 6	40–15	15–40	45	15–18	25–15	15–25	60
7–11	35–15	15–35	50	19–20	20–15	15–20	65
12–14	30–15	15–30	55	21	15	15	70

*Series P: Potash feldspar with the following analysis:

SiO_2	66.56
Al_2O_3	16.75
Fe_2O_3	None
CaO	1.65
MgO	0.25
K_2O	9.30
Na_2O	4.69
Ignition loss	0.5
	99.70

Series S: Soda feldspar with the composition:

SiO_2	66.12
Al_2O_3	17.96
Fe_2O_3	Trace
CaO	1.12
MgO	3.86
Na_2O	4.86
K_2O	5.18
Ignition loss	1.33
	100.43

Series C: Potash feldspar with addition of 1 per cent whiting.

†One-third North Carolina Kaolin, one-third Florida Kaolin, one-third Tennessee Ball No. 3.

III. EXPERIMENTAL DETERMINATION OF TRANSLUCENCY

12. *Preparation of Bodies.*—The composition of the bodies is indicated in Table 1. Kilogram batches of the extremes were ground in a small porcelain ball mill with porcelain balls for two hours, at a rate of 4375 revolutions per hour with a liter and a half of distilled water. Some of the bodies were also ground for twenty-four hours, and one for one hundred hours. Each slip was then lawned through a 120-mesh screen, and allowed to settle to a convenient working viscosity. The slips were blended, and trial pieces about three centimeters in diameter and four or five millimeters in thickness were cast in plaster molds.

A difficulty encountered at this point was the formation of air bubbles in the specimens. Every precaution was taken to reduce the number of these to a minimum. Some of the slips were allowed to stand under reduced pressure with an occasional gentle shaking. The results were not very satisfactory, since even after standing overnight they were not entirely free from bubbles. Moreover, the settling which occurred meanwhile necessitated stirring, with the danger of introducing more bubbles. Various methods of mixing were used, with the object of introducing a minimum of air. The slips were shaken, some were stirred in tall vessels and some in shallow vessels, but none of the results were very good. Thick slips had larger and fewer bubbles. One slip was boiled for a few seconds. This procedure removed the bubbles, but was objectionable since it changed the workability of the slip. The ideal solution of the problem of air removal would probably be to boil the slip, while very thin, under reduced pressure.

After being cast the specimens were air dried, reduced to the correct thickness with sand paper, and finally finished to a good surface with a cloth. The pieces were set in flint in a single sagger, and were burned to cones 10 and 12 in a gas-fired kiln. The firing above 1000 deg. C. was done at the rate of about fifty degrees an hour. After being cooled the pieces were cleaned, and the surfaces were lightly ground with emery to remove any adhering flint.

13. *Photometric Measurements.*—Some preliminary measurements of translucency were made with a photometer in order to obtain a check on those made with the photo-electric cell, and to get some idea of the relative accuracy of the two methods. An optical bench with a Lummer-Brodhum photometer box was used. The standard lamp was placed at one end of the bench, and a wooden, light-tight box, containing another lamp, at the other. A hole, a half an inch in diameter, was cut in this box just in front of the light, and a clamp was fastened over this hole so that a specimen could be held in front of the lamp.

The intensities of the two light sources were compared by moving the photometer box up and down the bench until the two concentric circles of light in the telescope were of equal brightness. If the distance of the box, when thus adjusted, from the standard lamp is d_s, and its distance from the unknown lamp d_u, and if the intensity of the standard is I_s and that of the unknown I_u, then I_u can be calculated from the equation

$$I_u = \frac{d_u^2}{d_s^2} I_s \tag{7}$$

The intensity of light I transmitted through the opening in the box was first determined without any specimen in the clamp. In order to find the total light incident upon the specimen L_i it is necessary to multiply the intensity I_i by the solid angle with the lamp filament as vertex subtended by the opening in the box

$$L_i = I_i \frac{A}{r^2} \tag{8}$$

where A is the area of the opening and r the distance of the opening from the filament. A specimen was then placed in the clamp and a new point of equilibrium obtained. From Equation 7 the transmitted intensity I_t is found. The assumption was then made that the transmitted light is perfectly diffused, that is, on looking at the specimen from the transmission side it appears equally bright in all directions, but the apparent area decreases with obliqueness of view. The total transmitted light on this assumption, as will be shown more in detail under the photo-electric cell method, is

$$L_t = I_t \pi \tag{9}$$

The practical measure of translucency is the ratio of L_t to L_i.

Photometric measurements of this character are rather unsatisfactory because of the difficulty of obtaining an accurate point of equilibrium when the two light sources have different colors. In most cases the light transmitted by porcelains is distinctly reddish, making it very difficult to compare with a whiter source of radiation. In general, the less the translucency, the redder is the transmitted light, so that it is difficult to compare two pieces when their translucencies differ greatly. In addition, the point of equilibrium of the photometer box should be near the center of the bench in order to give the best accuracy. It was impossible to accomplish this result because the translucency of all porcelains is very low in absolute value.

14. *Measurements with Photo-Electric Cell.*—Whenever any metal is subjected to ultra-violet light it emits electrons. This phenomenon is known as the photo-electric effect and the photo-electric cell is based on its action. The sensitivity of metals varies greatly, both with respect to the number of electrons emitted and the frequency of the radiation which will cause the emission. The alkali metals give off their electrons when subjected to visible light as well as to ultra-violet rays. The maximum velocity of the emitted electrons is independent of the intensity of the incident light, but the number of electrons per second is directly proportional to the intensity. The current of the cell, being proportional to the number of electrons emitted, will therefore be a direct measure of the intensity of the incident light. The results are not affected by temperature changes.

The cell used for this investigation was made by Dr. Jakob Kunz of the Department of Physics. The process of constructing the cell is as follows: A tube of the proper shape fitted with the necessary electrodes is first prepared. The bulb is then entirely silvered on the inside, except at one place to allow for the entrance of the light. Some potassium is

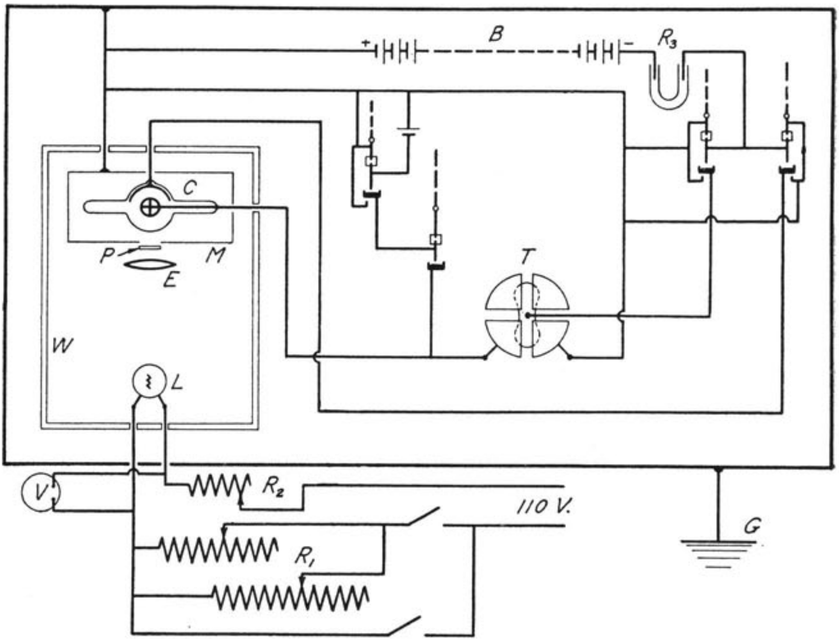

FIG. 2. CIRCUIT CONNECTIONS FOR MEASURING TRANSLUCENCY BY MEANS OF PHOTO-ELECTRIC CELL

introduced in one arm and the tube is exhausted to a high degree. The potassium is distilled into the bulb so as to cover all except the place for the entrance of the light. Hydrogen is then pumped in, and a discharge passed through the cell by means of an induction coil. The hydrogen reacts with the metal so as to increase the sensitivity. After this the hydrogen is pumped out and replaced by an inert gas, the pressure being adjusted so as to give the maximum sensitivity. The tube is finally sealed and is ready for use.

The amount of the current is of the order of 10^{-10} amperes for the small intensities obtained in translucency measurements. To measure this current a Dolezalek quadrant electrometer was used. The instrument was fitted with a rather heavy phosphor-bronze suspension. The electrometer was used heterostatically, that is, the needle was maintained at a constant potential (about 80 volts), one pair of quadrants was grounded, and the other pair connected to the positive electrode of the cell. The current was measured by the rate at which the potential increased, this being inversely proportional to the time required by the needle to swing between two fixed points.

The connections are indicated in Fig. 2. The photo-electric cell was mounted inside a small metal box *M*, which was provided with an opening in front of the cell *C*, and a clamp in front of the opening. The piece *P* to be tested was placed in this clamp. This box was placed in a larger wooden box *W* along with the standard lamp *L*. The filament of the lamp was kept about fifteen to twenty centimeters in front of the specimen and a lens *E* was interposed so as to make the light rays parallel. A difference of potential of about 80 volts was maintained across the cell by means of a number of small dry batteries *B*. The anode or wire grid was connected to the electrometer. When the cell was exposed to the light transmitted by the piece, it emitted electrons which gave rise to a current under the influence of the potential difference across the tube, and this in turn gave a gradually increasing positive charge to the quadrants of the electrometer. The deflection of the electrometer *T* was measured in the usual way by means of the reflection of a scale into a telescope from a mirror fastened to the needle.

In practice it was found convenient to give the anode of the cell an initial negative charge so that the entire length of the scale could be used if necessary. This gave the needle opportunity to establish a more uniform motion in its drift across the scale. Due to the inertia of the needle, the motion was invariably oscillatory when the current was applied suddenly. To overcome this difficulty there was placed in series with the lamp circuit a rheostat R_1 whose resistance could be varied gradually by a motor and a reducing gear. In this way the light was gradually turned on, with the result that the current slowly increased and the electrometer needle no longer received a sudden impulse. The standard lamp was lighted by direct current obtained from a generator. A small resistance R_2 was placed in series with the circuit so that, by changing it, the operator could keep the voltage constant at all times.

A water rheostat R_3 with about 100 000 ohms resistance was placed in series with the cell and the electrometer in order to protect the batteries from short circuits and to prevent possible damage to the cell.

In order to protect the apparatus from external static disturbances all the instruments were enclosed in a wire cage. All changes in the circuits were then made by means of electrometer keys of special design which could be operated by strings from the outside of the cage. These keys were two-way switches insulated with amberoid. Proper insulation of the apparatus was the most troublesome difficulty encountered. Ordinary insulators were useless. In the summer time it was found necessary to enclose all the terminals and leads in air-tight metal boxes and tubes, which were kept dry on the inside by means of calcium chloride or phosphoric anhydride.

In making measurements it was found that over a considerable interval of time the constants of the instruments gradually changed. To compensate for this control readings were made about every half hour. Corrections were also made for the leakage current.

In order to maintain the rate of deflection of the electrometer within limits which could be accurately measured with a stop-watch it was necessary to use lamps of different sizes for specimens greatly differing in translucency.

The ratio of corrected currents for any two specimens represents their relative translucency. In order to find the absolute translucency it was necessary to obtain a reading without any piece between the lamp and the cell. To do this, a hole was made in a piece of tin foil of such a size that when the opening to the cell was covered by the foil, a proper rate of deflection was obtained. The total incident light L_i was then proportional to the mean of these deflections multiplied by the ratio of the area of the opening in the box to the area of the hole in the foil.

The light passing through the hole in the tin foil consisted of rays which were parallel or nearly so. Therefore, all the light passing through the tin foil opening entered the cell and was effective in producing a current. With the porcelain specimen in position the transmitted light was diffused and only a portion entered the cell, depending on the area of the sensitive layer and the distance of the layer from the specimen. In order to calculate the total transmitted light it was assumed that there was perfect diffusion, so that to an observer looking at the piece it would appear equally bright at all angles . The total light transmitted in any direction would therefore be proportional to the apparent area seen by the observer or in other words proportional to the cos θ where θ is the angle between the perpendicular to the specimen and the rays to the observer. If all the light coming from the piece at an angle of less than θ_1 from the normal enters the cell then, on the foregoing assumptions, the ratio of the total transmitted light L_t to that measured by the cell L'_t is

$$\frac{L_t}{L'_t} = \frac{\sin^2 \frac{\pi}{2}}{\sin^2 \theta_1} = \frac{1}{\sin^2 \theta_1} \tag{10}$$

TABLE No. 2

TYPICAL RESULTS WITH PHOTO-ELECTRIC CELL

Composition	Piece	Thickness, mm.	Translucency per cent	Translucency per cent for 1 mm.
Series S Cone 10 No. 1	1	1.57	0.530	2.16
	2	1.60	0.482	2.12
	3	1.62	0.377	1.88
	4	1.65	0.380	1.97
	5	1.71	0.366	2.12
Series C Cone 12 No. 8	1	1.50	0.0207	0.23
	2	1.54	0.0168	0.22
	3	1.55	0.0217	0.26
	4	1.62	0.0125	0.23
	5	1.69	0.0157	0.32

15. *Results.*—Individual readings with the photometer varied considerably, but by taking the average of a large number of readings the error was reduced to a reasonable amount. The results were checked by using lamps of different candle power behind the same specimen, and using different lamps for comparison. In this way it was shown that within the limits of experimental error translucency is independent of the intensity of the incident light. In general, relative translucencies found by this method will be in error by less than ten per cent of the total, and absolute translucencies will be of the correct order of magnitude. Experience gained in these tests indicates that for deciding which of two pieces is the more translucent, direct visual examination can not be much excelled by any other method, but it is impossible to make any estimation of the magnitude of the difference in that way.

By means of the photo-electric cell it was possible to determine accurate relative values of translucency. It was found, however, that the absolute values of translucency as determined by the cell were lower than those determined by the photometer. This is illustrated in Fig. 3, where curve A shows the relation between translucency and thickness as determined by the photometer, and curve B the same relation as determined by the photo-electric cell. Curve A was calculated from Equation (5), using the values $\alpha = 0.065$ and $R = 0.60$; curve B was calculated using $\alpha = 0.0091$ and $R = 0.75$. The points on the diagram were obtained by direct observation. The large difference between the absolute values of translucency, as obtained by those two methods respectively, is due to the greater sensitivity of the cell to the blue end of the spectrum than to the red. Since the proportion of red light transmitted by porcelains increases as the translucency increases, the

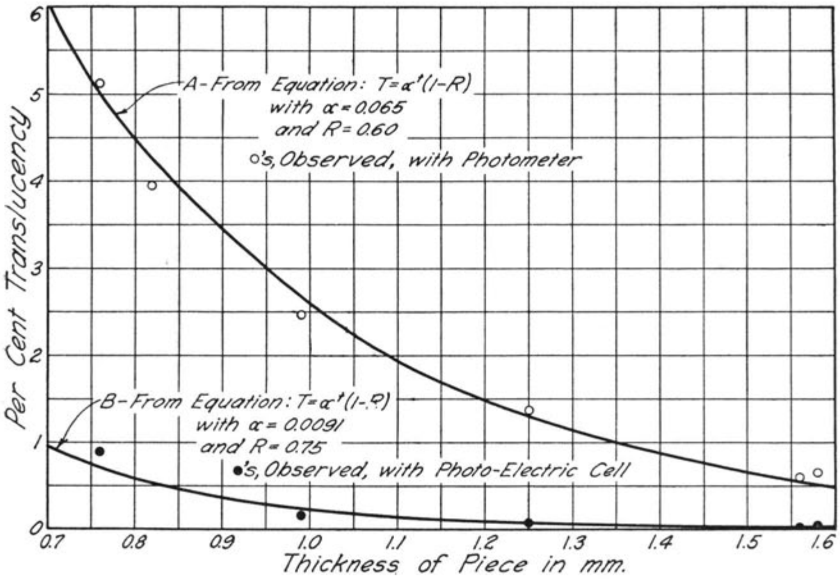

FIG. 3. RELATION OF TRANSLUCENCY TO THICKNESS OF SPECIMEN

translucency as obtained by the cell increases more rapidly with a decrease in thickness than that found by the photometer. This could be overcome to a large extent by the use of the caesium cell in place of the potassium cell.

The results found for specimens of two typical compositions are given in Table 2. It is seen that the greatest error is due to variation between the individual specimens of the same composition. Measurements with the cell on the same specimen usually did not vary more than 1 or 2 per cent from the mean, but due to difficulty in determining some of the constants involved, the absolute values can only be claimed to be of the correct order of magnitude. It should be emphasized that in order to obtain a reliable value for the relation between composition and translucency, the mean value for several specimens must be used. In Fig. 4 is shown the mean value of the translucency for $t = 1$, as calculated from Equation 5. Four or five specimens of each composition were measured by the cell and the value of α calculated for each on the assumption that $R = 0.75$. The mean of these values of α was then used in finding T for unit thickness.

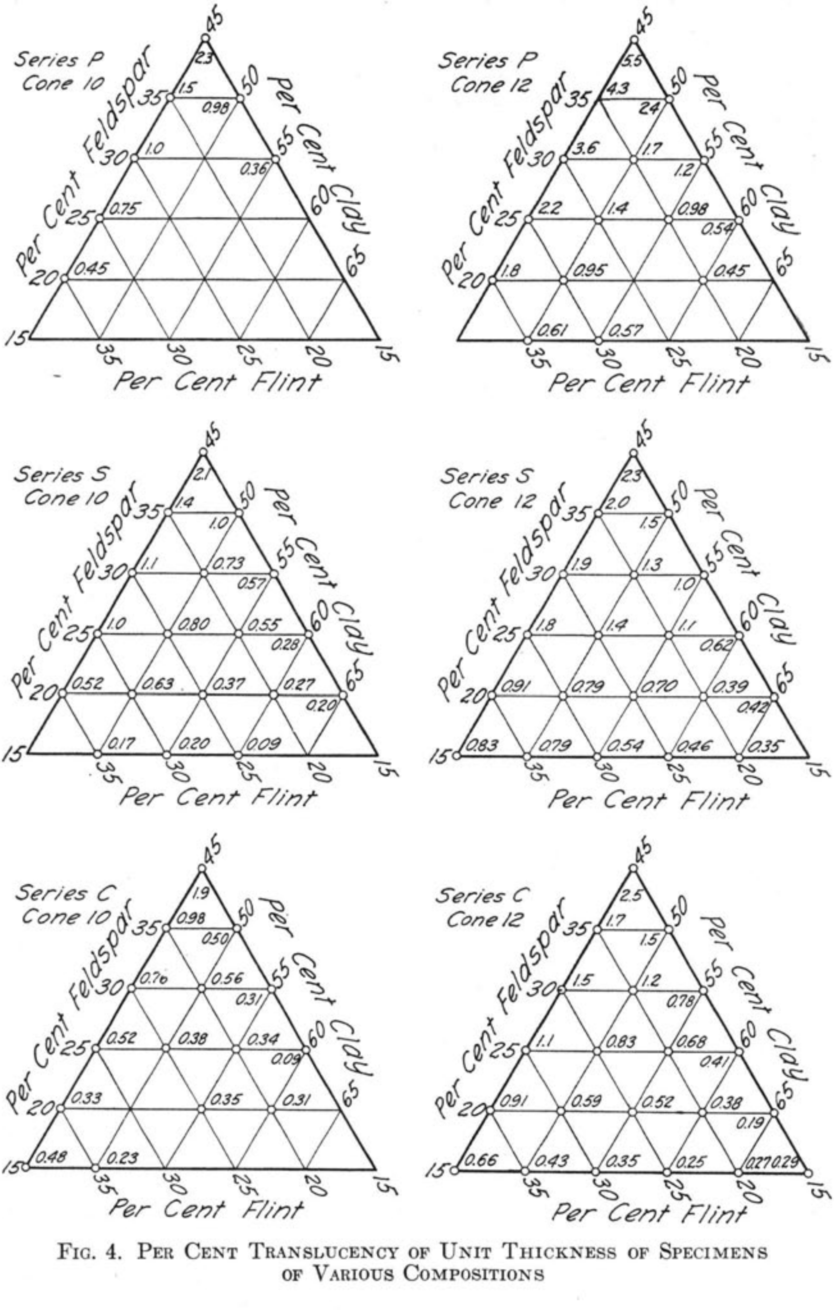

FIG. 4. PER CENT TRANSLUCENCY OF UNIT THICKNESS OF SPECIMENS OF VARIOUS COMPOSITIONS

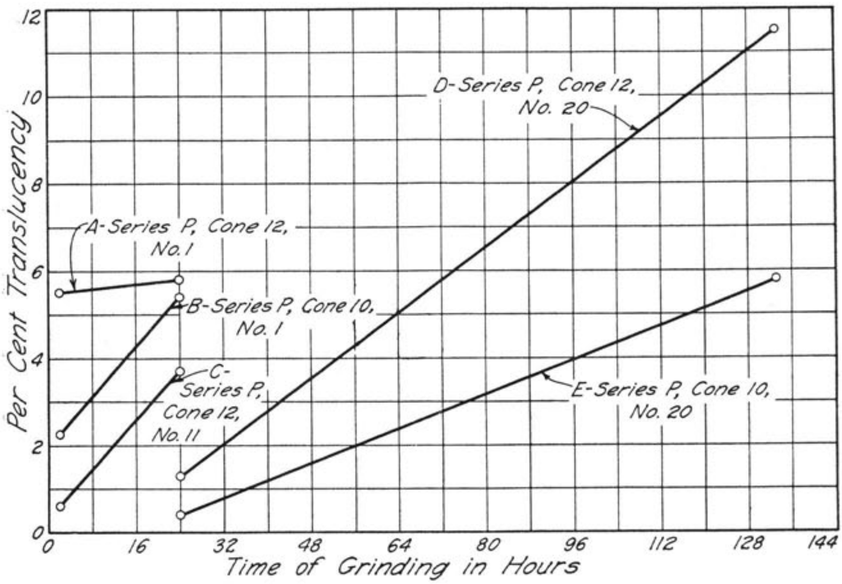

FIG. 5. RELATION OF TRANSLUCENCY TO AMOUNT OF GRINDING OF SLIP

The results show clearly that, in the field investigated, addition of flint increases translucency considerably, but addition of feldspar increases it still more rapidly. The effect of the addition of $CaCO_3$ and of the substitution of a feldspar high in soda for one high in potash was apparently obscured by a variation in the clay used. Series S and C were made up some time after Series P, so that the stock ball clay probably varied considerably in the mean time. In every case, however, it is seen that the relative effects of clay, flint, and feldspar are the same. An increase in temperature also increases the translucency, as would be expected. Another very striking factor in increasing translucency is fine grinding of the body. The effect of this is illustrated in Fig. 5 which shows the translucency of pieces of the same composition which have been subjected to different amounts of grinding.

IV. CONCLUSIONS

16. *Conclusions.*—As a result of the measurement of over 400 specimens by means of the methods described the following conclusions were reached:

(a) Variation among individual specimens of the same composition are so large that it is necessary to take the mean results from several specimens in order to obtain trustworthy values of translucency.

(b) Translucency is not inversely proportional to the thickness of the specimen.

(c) The relation between translucency and thickness is not a linear one, as was formerly supposed, but an exponential one.

(d) In bodies composed of clay, feldspar, and flint, those with the highest feldspar content have the highest translucency and those with the highest clay content the least. This is true at any temperature at which the bodies are translucent.

(e) In bodies of this character and containing a given feldspar content, the best translucency is always found with the higher content of flint.

(f) If the clay content remains constant, the higher translucency is found with an increase of feldspar at the expense of the flint.

(g) If the flint remains constant the higher translucency is found in the bodies in which the feldspar is increased at the expense of the clay.

(h) Increase of burning temperatures gives increase of translucency.

(i) Fine grinding of bodies gives a very striking increase in translucency at the temperatures used.

(j) The introduction of CaO in the form of calcium carbonate in the amounts used does not appear to be of advantage inasmuch as both the bodies made with soda feldspar and potash feldspar showed superior translucency at the temperatures used.

It would be highly desirable to have a set of porcelain specimens carefully prepared and standardized by means of an improved photoelectric cell method, so as to obtain a series of well-determined absolute translucencies. If this were done, these standard specimens could be easily duplicated and these secondary standards could then be distributed in the industry. It would then be a simple matter to find the translucency of any ware by mere visual comparison with these standards, since differences in relative translucency can be very accurately determined by the unaided eye.

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