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THE LAWS DETERMINING THE BEHAVIOR OF GOLD IN FUSING AND CASTING.

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SELDOM if ever, in the history of the progress of dentistry, has so much confusion and uncertainty accompanied both the practical results of an important mode of procedure, and the interpretation of the processes involved, as has attended the operations involving the fusing and casting of gold, and particularly the cast gold inlay. This confusion has been occasioned by the fact that the fundamental physical properties, first, of the gold itself, and second, of the accessories to its use, were not known to any branch of science; and the existing troublesome errors and the confusion attending their interpretation cannot be corrected until these physical properties are known, and the laws under which they operate are heeded.

THE VARIOUS METHODS OF MANIPULATING GOLD OR ITS ALLOYS IN CASTING.

It will be necessary for us to have very clearly in mind, while studying the laws underlying these processes, the physical conditions and procedures in detail that are made use of in the various methods of manipulating the gold, for they establish the fixed conditions with which we have to deal. These are as follows:

(1) The fusing of gold or an alloy of gold directly on to a higher-fusing metal, as in soldering a bridge with and without an investing medium.

(2) Taking an impression of a cavity or other surface in thin platinum foil, and fusing gold directly into it.

(3) Making a pattern of wax in the cavity and removing it and investing in some refractory material, and then, after burning out the wax, casting the gold directly into that cavity in the investment.

(4) Making an impression of the tooth cavity and surface beyond the cavity, and making a model in this of a material which is refractory enough and strong enough to cast directly on, after

waxing up the cavity in the model, and investing the model and wax in a plaster and silica investment material.

(5) Making an impression of the tooth cavity and surfaces beyond the cavity as in the last method, then making a model of fusible metal or amalgam or sulfur, into which the gold cannot be cast directly, then making a wax pattern in that model, which is removed and invested as in the third method, and the casting made into the investment.

FACTORS OF ERROR.

Some of the confusing and conflicting effects are as follows:

First and chiefest is the decreased size of the gold reproduction due to its own contraction.

Second: It may be distorted, or unevenly decreased or increased in size.

Third: It may have a depression or hole in its surface.

Fourth: It may seem to be enlarged.

Fifth: It may be distorted or out of proportion.

These conditions have been caused by changes occurring in the materials involved in the procedure, and the methods of using them.

The variable factors that have a part in producing these possible errors are—

(1) Change in the dimensions of the impression or the pattern by the cooling when removing.

(2) Change in the dimensions of this impression or pattern material by change in temperature when investing.

(3) Change in the shape of the pattern due to the elasticity of the wax.

(4) Change in the dimensions of this investing medium in its process of setting.

(5) Change in dimensions of this investing medium in the process of heating, or heating and cooling.

(6) Effects of the wax or pattern material on the investing medium.

(7) Change in the investment dimensions from the pressure of the gold when casting.

(8) Action of the molten gold on the investing medium.

(9) Change in the dimensions of the gold with its change of state from liquid to solid.

(10) Change in the dimensions of the cooling gold.

(11) Distortion of the mold in the investing medium by the cooling gold.

(12) Stretching of the gold if held when cooling.

While all of these variable factors are essential contributors, to a larger or smaller extent, to the final error, none plays so important or large a part in the average technique as the change in the dimensions of the cooling of gold; and all efforts to determine the extent of error caused by the cooling gold, when any or all of these other variable factors are present, have apparently been not only unsuccessful, but extremely misleading, for the results have been the sum total of all the involved errors.

FACTORS OF ERROR IN THE TAGGART DIRECT METHOD.

To illustrate, let us follow *seriatim* the steps of the Taggart direct method technique. The wax for its pattern is put in the cavity at its workable temperature, which will be for the various inlay waxes from 95° to 130° F. It is cooled in the cavity, to render it firm and strong, to about 67° F., and in so doing it contracts, according to its formula, one or two per cent. of its lineal dimension. If invested at this temperature an error of this definite amount is already carried forward, to appear in the final inlay, unless it be corrected by some other step. If the wax of the pattern, when being formed and cooled, surrounds the tooth structure, covering outside dimensions, it will be stretched as it cools, and it would by so stretching apparently correct part or all of the error of contraction from cooling; but all waxes have elasticity and hence do not remain stretched, which introduces a new uncertainty or error to change the accumulated error. When the wax pattern is invested, its temperature

will determine partly its dimension, for on heating from 67° F. to 100° or to 130° F., the wax will be expanded, and if not carried to the softening point at which surface tension will distort it or where the investment will change its shape, part or all of the accumulated error due to contraction of the wax may be corrected, and with a certain definite technique to be explained later, even an error of expansion produced. The ordinary technique will not show the true expansion. Heating the pattern to enlarge it will release its elasticity and allow much distortion.

In the next step, of heating the investment material, if it be of the best quality we may have an expansion of about one per cent., or if of poor quality we may have a contraction of two per cent., according to our manipulation, and if the investing compound is soft and yielding it can be distorted easily by the pressure of the gold when casting, thus causing an error which is not a uniform expansion.

When the molten gold is forced into the investment, its physical state changes from liquid to solid, and here we have what has heretofore been an entirely unknown factor, but which we will show later to be a very large contraction; and again, on changing temperature from its freezing-point and cooling to normal temperature, it contracts, as the writer has previously shown, over two per cent. (*Items of Interest,* May 1908.) This contraction can be partially controlled by pressure on the congealing gold, thus forcing gold from the sprue, and partially by holding the gold as it contracts, *i.e.* by causing it to surround a strong form, thus preventing the normal contraction.

The relation of the size of this final casting of gold to the original cavity in which the wax pattern was made may thus vary through a wide range, and the final error is the sum of all the plus and minus changes made in the size of the record of the cavity, as it passed through the different materials and processes. We will show definitely the amount of change produced by each step.

BEHAVIOR OF THE INDIVIDUAL MATERIALS USED IN CASTING.

To work intelligently we must therefore know the behavior of the materials used for each step, and make the unfixed or variable changes correct the fixed changes. The great fixed change is the contraction of the gold both as it changes its state and as it cools to normal temperature, and these changes will have the largest consideration in this paper, but the other factors are essentials, and must also be definitely established for the fixing of fundamental rules of procedure. We will take them up in sufficient detail in the order of their occurrence in the technique of procedure.

The making of relatively exact determinations requires instruments of very great precision. The writer has had several constructed especially for this research work, and has had very great assistance from Prof. Dayton C. Miller, professor of physics in the Case School of Applied Science, whose services he was fortunately able to engage with the use of very special instruments of precision for the most complicated of these determinations.

FACTORS OF ERROR INVOLVED IN THE IMPRESSION OR PATTERN MATERIALS (WAXES).

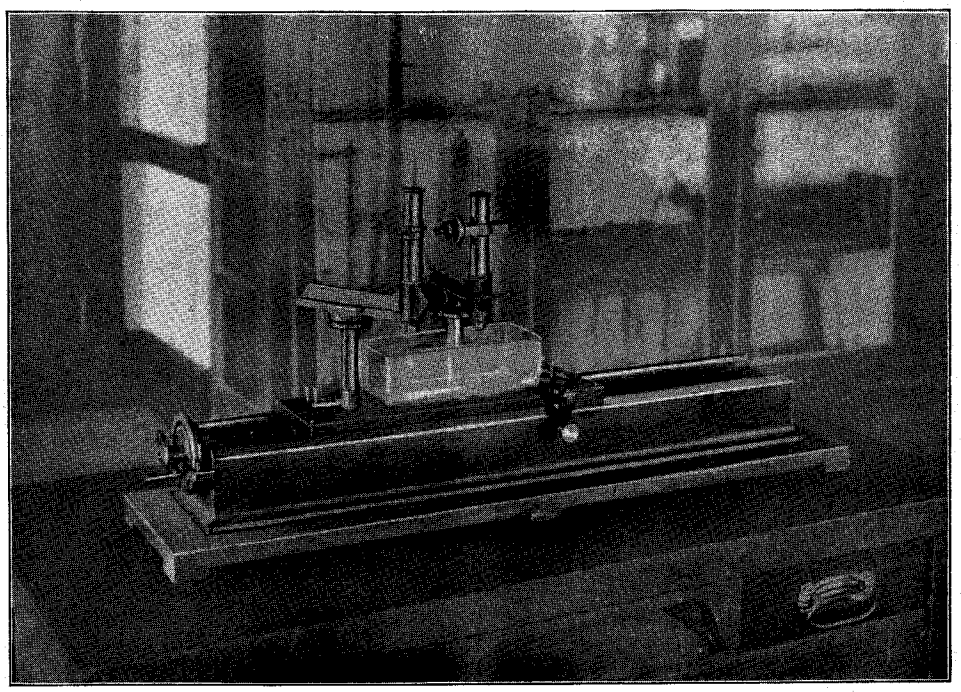
We will study the materials and uses in their order of sequence. First: The change in the dimensions of the impression or pattern material by cooling when being removed from the cavity. Practically all the kinds of impression or pattern material used for inlay work for carving in the cavity have about the same qualities, and the working range in temperature varies according to the base used in largest proportion in their manufacture.

The carving waxes are not best adapted for taking impressions for any of the model methods. The following waxes purchased in the open market, and the base waxes chiefly used in them, have been carefully tested for their expansion co-efficient, working range, and total ex-

pansion from 67° F., room temperature, to their maximum working temperature: Bird & Moyer, Cleveland Dental, Klewe's, Consolidated, Peck's, Price's for Stone Model Method, S. S. White black, S. S. White Crown Sticky-wax, Standard, and beeswax, gum damar, paraffin, stearic acid, bayberry, canawba, and cerecin.

The rate of expansion of all waxes changes rapidly with increase of temperature, but at different rates for different base waxes and different formulæ or mixtures. This made it necessary to determine very close steps for all the waxes. This was done by two methods, one by measuring the expansion directly with a microscope comparator (shown in Fig. 1). The wax bar is heated in a water-bath and the distance between the pilot points or hair lines that are placed on the wax bar is measured by micrometer screws, these carrying two microscopes which are focused on them. The other method was by measuring the density of the waxes at various temperatures, which gives the volume expansion. The linear expansion is one-third the cubical expansion. Fig. 2 shows the small balance arranged for these determinations. The weight of the wax was measured, while suspended in the beaker of water, at different temperatures. Table I gives the linear expansion, in thousandths of an inch, and the density at various temperatures Centigrade of the various waxes. Table II gives the working ranges of the various waxes and the changes in their dimensions, in thousandths of an inch, with changes of temperature Fahrenheit. This table is a very valuable one, inasmuch as it gives the key to much of our error. The lower or minimum working range of temperature of the various waxes can be modified slightly by working the wax. The maximum temperature is usually higher than

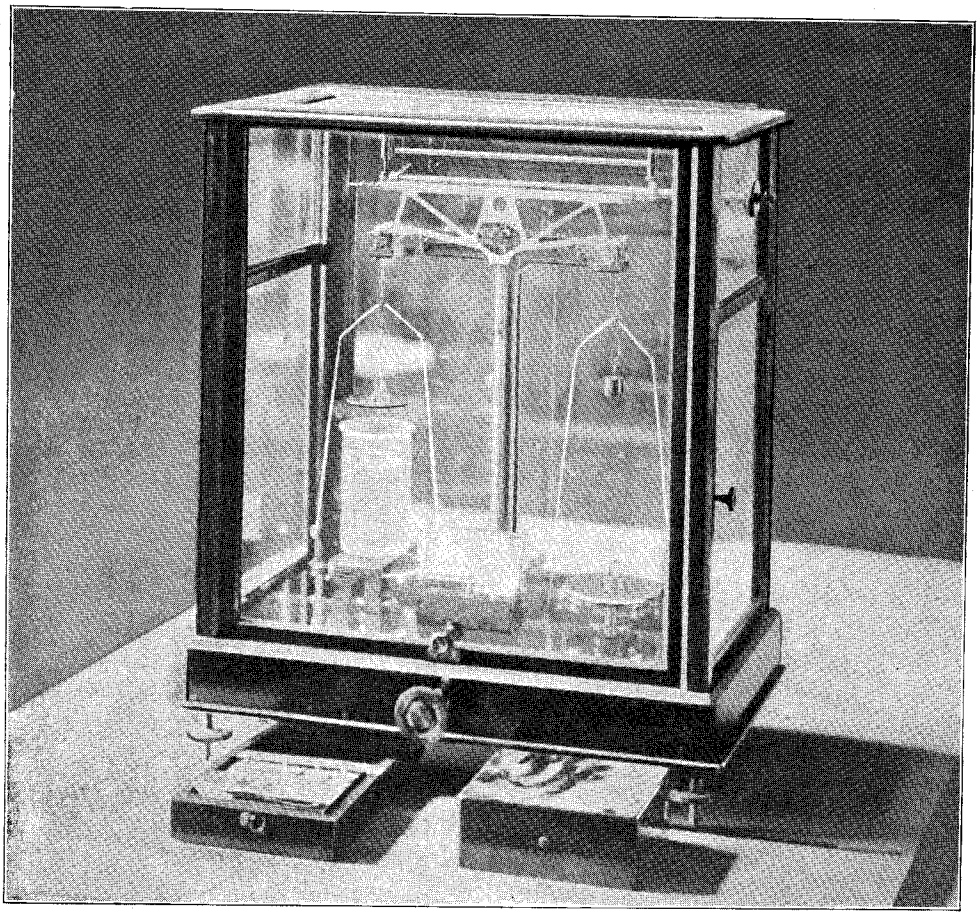
FIG. 1.



Microscope comparator arranged for measuring expansion of wax.

that at which a frail pattern of wax could be handled and keep its shape, though a block of it could. In Table II the inlay waxes of the market are arranged alphabetically. It also shows the elasticity when a bar of wax is bent one inch, also one-half inch, at its lower working range, and chilled, then heated to the upper working range, when it will return nearly to its former position. If a wax, say the first one, be placed in a cavity at its minimum working temperature, 107° F., and cooled down to 67° F., it will contract 12/1000 of its linear dimensions, or 1.2 per cent., which will be the error carried forward if it be invested at this temperature. If, however, it be heated at the time of investing, and placed in an investment at 130° F., its maximum working temperature, it will expand 36/1000, or 3.6 per cent. The latter dimension is 24/1000, or 2.4 per cent., larger than when the impression wax was in the cavity. And so the behavior of all other waxes is indicated. This would seem to be a means for correcting, by compensation, all of our difficulties due to the contraction of the gold,

FIG. 2.



Small balance arranged for measuring density of wax and gold.

TABLE I.

Expansion and Density of Waxes.

Linear expansion (E) *in thousandths of an inch, at various temperatures—Centigrade* (*t*) *and Fahrenheit* (*T. F.*).

	Price's Impression Wax.		Cleveland Dental Special Carving Wax.		Consolidated Dental Mfg. Co. Casting Wax.		Peck's Gold Inlay Wax.		Bird & Moyer Inlay Wax.		S. S. White Inlay Model Wax.		Standard Inlay Wax.		S. S. White Crown Sticky-Wax.		Klewe.		Damar.		Beeswax.		Japan Wax.		Paraffin.	
	Brown.		Green.		Black.		Red.		Blue.		Black.		Gray.		Pink.		Red bar.									
	Density at initial temperature—19.4° to 20.0° F.:																									
	1.033		*0.915*		*0.901*		*0.951*		*0.943*		*0.971*		*0.962*		*1.025*		*0.927*		*1.040*		*0.968*		*0.990*		*0.937*	
T. F.	*t*	E	*t*	E	*t*	E	*t*	E	*t*	E	*t*	E	*t*	E	*t*	E	*t*	E	*t*	E	*t*	E	*t*	E	*t*	E
67	19.7	0.	19.5	0.	19.4	0.	19.5	0.	19.5	0.	19.5	0.	19.5	0.	19.5	0.	19.7	0.	19.8	0.	19.8	0.	19.9	0.	20.0	0.
87	30.8	3.3	29.3	4.9	30.1	6.2	29.9	5.8	29.6	2.8	29.6	11.6	29.4	3.3	29.3	1.0	30.6	2.2	30.4	0.9	30.2	3.5	30.3	3.0	30.2	5.3
95	35.1	5.9	34.4	10.2	35.5	10.7	35.1	8.6	34.7	7.5	34.6	15.4	34.5	6.4	34.3	2.2	35.0	4.9	34.8	1.8	34.6	4.8	34.4	4.5	34.4	8.8
105	40.7	8.2	40.4	11.7	40.3	13.1	40.1	10.7	39.6	10.1	39.6	17.0	39.5	8.9	40.0	4.9	40.5	7.6	40.1	2.7	39.8	7.5	39.6	6.5	39.4	11.8
113	45.0	Soft 10.4	44.3	13.0	45.0	16.4	44.8	14.7	45.6	14.9	45.1	21.1	44.6	12.4	44.1	8.1	44.8	12.0	44.1	3.4	45.0	12.0	44.8	10.7 Crumbles	44.4	16.0
122	50.0	Melted	50.6	23.1	50.4	19.7	50.0 Crumbles	27.1	50.1	24.8	49.6	31.0	49.2	22.7	49.9	13.9	50.9	15.6	50.1	3.8	49.7	18.0	49.5	19.5	48.5	Soft 22.8
131	. . .	. . .	Crumbles 53.1	35.2	Crumbles 54.9	27.9	. . .	. . .	Crumbles 54.4	36.5	Crumbles 53.8	41.3	Crumbles 54.3	30.5	Bends very easily 52.5	14.8	54.8	20.7	53.3	4.2	54.2	24.5	. . .	. . .	50.0	Too soft to handle
134	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	56.7	24-5	57.9	4.9	55.9	28.0	. . .	. . .	. . .	. . .
140	. . .	. .	. . .	. . .	. . .	. .	. . .	. .	. . .	. .	. . .	. . .	. . .	. . .	.	. . .	Crumbles 59.7	28.8	60.3	5.8	Crumbles 59.0	32.5	. . .	. . .	. . .	. . .
147	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	64.3	6.7	. . .	. . .	. . .	. . .	. . .	. . .
150	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	66.0	5.8	. . .	. . .	. . .	. . .	. . .	. . .
156	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	Flows 69.9	5.8	. . .	. . .	. . .	. . .	. . .	. . .

TABLE II.

WORKING RANGES OF IMPRESSION WAXES, AND THE CHANGES IN THEIR LINEAR DIMENSIONS WITH CHANGES OF TEMPERATURE.

NAME.	WORKING RANGE.		LINEAR EXPANSION AND CONTRACTION PER INCH IN THOUSANDTHS, ALSO AS PER CENT.						ELASTICITY CHANGE OR RETURN OF BEND AFTER HEATING TO HIGHER TEMPERATURE.	
	Minimum temp. in ° F.	Maximum temp. in ° F.	Contraction from lowest working range to 67° F.		Expansion from 67° F. to highest possible working range.		Difference or maximum possible excess of expansion over contraction.		½ inch bend.	1 or 2 inch bend.
			Thousandths.	*Per cent.*	*Thousandths.*	*Per cent.*	*Thousandths.*	*Per cent.*		
Bird & Moyer inlay wax . .	107°	130°	12	1.2	36	3.6	24	2.4	50 per cent.	50 per cent.
Cleveland Dental inlay wax .	109°	128°	12	1.2	35	3.5	23	2.3	50 " "	62 " "
Klewe's inlay wax	115°	139°	12½	1.25	28½	2.85	16	1.6	50 " "	60 " "
Consolidated inlay wax . .	115°	131°	15	1.5	28	2.8	13	1.3	50 " "	50 " "
Peck's inlay wax	112°	122°	14	1.4	27	2.7	13	1.3	75 " "	50 " "
Price's for stone model method	98°	113°	6	0.6	10	1.0	4½	0.45	25 " "	10 " "
S. S. White (black) inlay wax	115°	129°	23	2.3	41	4.1	18	1.8	50 " "	50 " "
S. S. White (crown sticky) inlay wax	106°	126°	10½	1.05	15	1.5	5½	0.55	50 " "	40 " "
Standard inlay wax	110°	135°	11	1.1	31	3.1	20	2.0	50 " "	50 " "
Beeswax	94°	138°	5	0.5	32½	3.25	27½	2.75	. . . . .	. . . . .
Gum damar	melts at	160°	. .	. .	. .	. .	. .	. .	. . . . .	. . . . .
Japan wax	"	122°	. .	. .	. .	. .	. .	. .	. . . . .	. . . . .
Paraffin	100°	120°	10½	1.05	22½	2.25	12	1.2	. . . . .	. . . . .
Stearic acid	melts at	150°	. .	. .	. .	. .	. .	. .	. . . . .	. . . . .
Canawba	"	205°	. .	. .	. .	. .	. .	. .	. . . . .	. . . . .
Cerecin	"	122°	. .	. .	. .	. .	. .	. .	. . . . .	. . . . .
Bayberry	"	134°	. .	. .	. .	. .	. .	. .	. . . . .	. . . . .

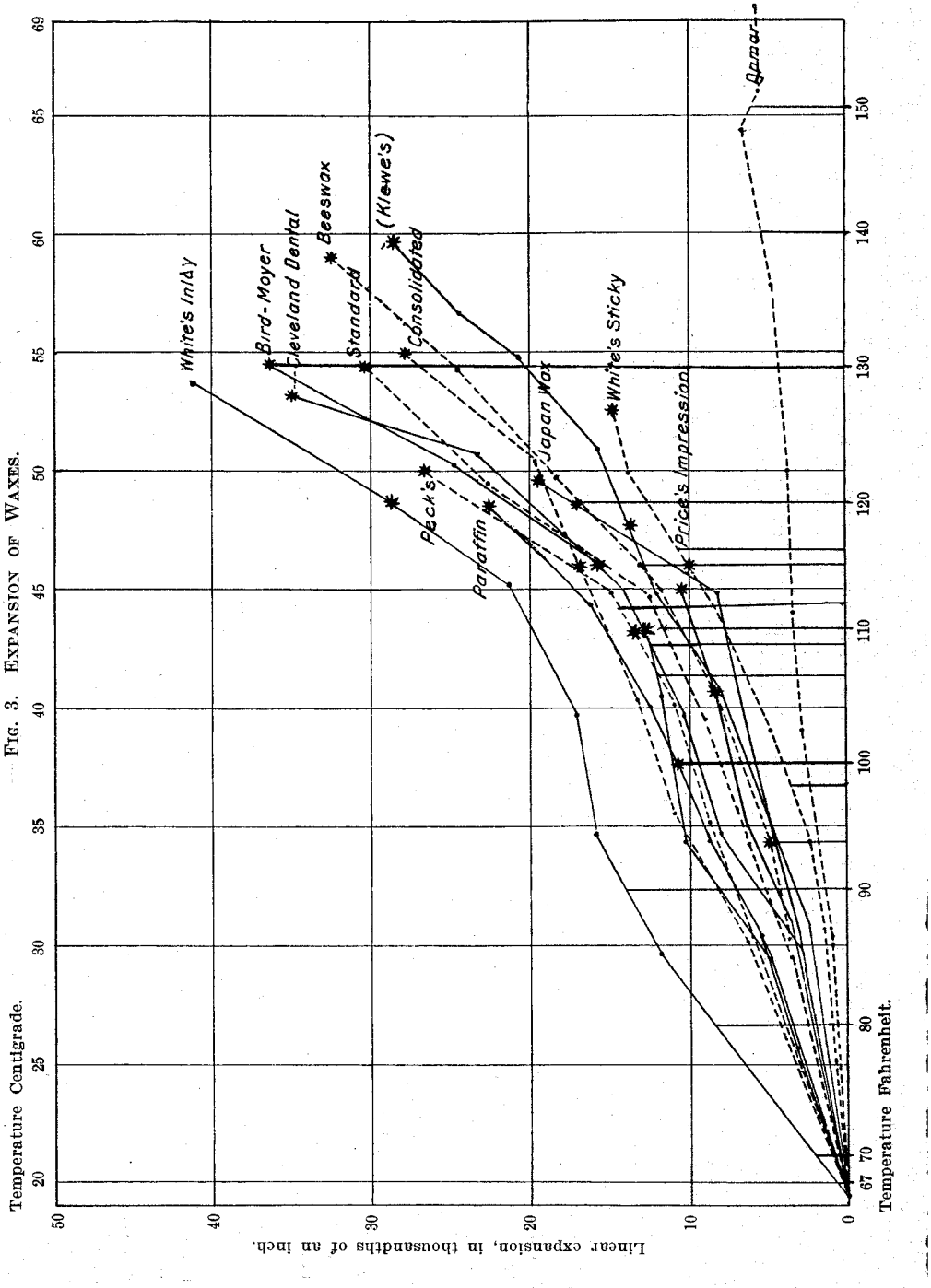


FIG. 3. EXPANSION OF WAXES.

but it does not, as will presently be shown. Fig. 3 shows diagrammatically the exact expansion of all the different waxes from 67° F., or its equivalent 20° C., to any temperature up to the limit of its working range. It also shows graphically the relative behavior of all the different waxes tested. The base line, reading from left to right, indicates the progressive increase from 67° in temperature in units Fahrenheit, and the top the corresponding temperature in units Centigrade from 20°. The elevation of the curve as shown by the figures on the left side reads the linear expansion, in thousandths, of its dimension, or can be read in hundredths, as per cent., by leaving off the second cipher. From this chart can be seen at a glance the exact change in dimension of any of the waxes between any two temperatures between 67° F., and its working limit. All waxes are taken as zero dimension at 67° F., or 20° C., temperature. It will be noted how the increase in the rate of expansion with the increase of temperature is shown by the lines deflecting upward more rapidly as the temperature increases. These determinations are made on samples of cast wax, to avoid the errors of elasticity which form the most treacherous error we have to contend with, and which I fear that few have either suspected or recognized. If you will take a bar of any of the above waxes, warm it in a bath to its working temperature, bend it and hold while chilling, and when it has become thoroughly cold release it, you will find that it will apparently remain bent. Upon being very slightly warmed, however, it will straighten again. Most of the above waxes are too brittle to allow of bending a straight cast bar into a hoop, but even the brittle ones have a large elasticity. If a bar or stick of the Cleveland dental inlay wax be warmed enough to bend into a circle until the ends touch, then chilled while held, and then warmed again, it will straighten one-third of the way to straight; and if again bent till the ends meet, chilled, and then warmed, it will straighten over 70 per cent. of the last bending. S. S. White sticky-wax will, when treated in the same way, straighten 79 per cent. of the distance of the second bending. The brittle carving waxes are Peck's, S. S. White, Bird & Moyer, Standard, and Consolidated, and all these have a large elasticity. When a stick of each, three inches long, is bent one-half inch from straight, held while cooling and then released, it will straighten again, usually about half way to straight, but this differs with the different waxes and temperatures when bent. The last column of Table II shows the amount, expressed in percentage, of the elasticity or return of wax bars bent both one-half inch and either one or two inches, as they would stand—for the brittle carving waxes would break before bending two inches.

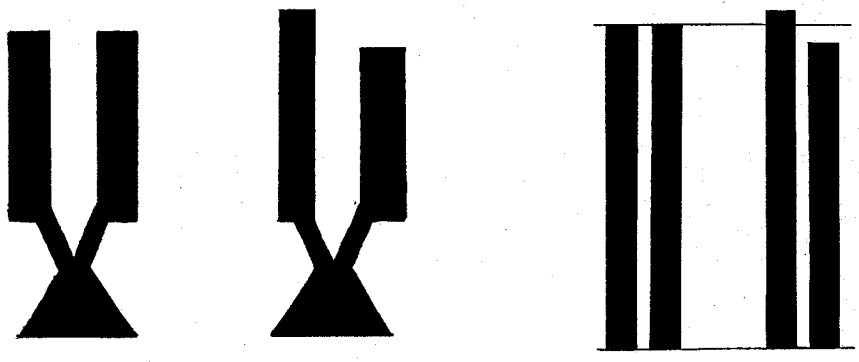
The error that is possible from this source is enormous, and it will always be a distortion, not a uniform expansion or contraction, therefore it cannot be corrected by another step. For example, see Fig. 4, A and B. If two wax bars of Cleveland dental inlay wax, or of almost any wax on the market, are heated to the lower working range, one being pulled or stretched while chilling and the other pushed endwise or compressed (both just as the wax could be in a cavity) each then being chilled while held, and then carved to be identical, they represent the same size and form, in this case one inch in length. If while chilled they had been placed in the cold investment, attached to the same sprue and cast, the bars would be identical, but when simply the change was made of placing them in a warm investment at their upper working range, and they were then cast, the difference in their length was 0.185 of an inch, or a variation of 18½ per cent., for the warming will release the elasticity, and thus the stretched bar will shorten 0.1, or 1/10 in., and the compressed one will lengthen 0.085, or 85/1000 in. Each will change its length by 10 per cent. or nearly so. These bars so treated and cast are shown in Fig. 4, showing A the wax before and B the metal after investing and casting.

This is a source of exceedingly large error—and it is not necessary that the

wax be placed in warm water as in a warm investment, for even the warm summer temperature or that of a warm room is sufficient. For example, two bars of a commercial inlay wax were taken, and one was stretched and the other compressed endwise, at the lower working range, and chilled while held. They were then cut to the same length, namely, 4.31 in., and attached to a card and left in a warm part of the room over night, and were measured when cold in the morning. The stretched one was shortened 0.25, or $\frac{1}{4}$ in., or 6 per cent., and the compressed one was lengthened 0.19, or 3/16 in., or $4\frac{1}{2}$ per cent. These are shown in Fig. 4, marked C, before, and D, after warming.

This part of the paper should embrace a more extended review, but space will not permit of it. Anyone can make these and other simple experiments to demonstrate that the elasticity of the wax may be and is a vary large source of error, especially in hot weather. When wax is melted into a form or chilled from the liquid state without pressure, its elasticity is negligible on warming again, though its original contraction is enormous. A comparison of patterns made both in cast wax and in worked or stretched wax is essential here, also a study of the effect of stretching the wax over a form (as in a double compound cavity), and the conflicting of the forces of expansion and elasticity, which are beautifully demonstrated as follows: If a bar of wax be heated and thus expanded, and then fastened to make it retain that expansion (as when a warm wax pattern is made by the direct method in a double compound cavity—a mesio-occluso-distal cavity in a molar), and then cooled, the wax will be stretched owing to being held in each case, and if chilled and kept chilled will remain frozen in that position, but if warmed will not expand from that position, but will contract, owing to its elasticity, a large part of the amount to which it has been stretched. Let us make two bars of wax, an inch long—of, for instance, Cleveland dental inlay wax—precisely alike in cold dimension except that one is carved directly from the cast wax stick and the other from a piece of the same wax that has been worked when warm and stretched as it chilled. The pattern pieces are then attached to the same sprue gate and invested together in an investment of plaster and silica at a temperature of 128° F. The piece cut from the unworked cast wax will expand 35/1000, or 3.5 per cent., and the other will, while

FIG. 4.



Two similar wax bars placed in a warm investment and cast. A, Before heating. B, After heating.

Two similar wax bars, showing elasticity distortion when heated. C, Before heating. D, After heating.

expanding, contract endwise the amount of its elasticity, an even greater amount. If after burning out the wax we cast pure gold into them both at the same time, we shall have bars differing greatly in length, though the wax patterns from which they were made were identical. One test of the above produced a bar of gold from the unworked cast wax 27/1000, or 2.7 per cent. longer than the pattern, and the other 67/1000, or 6.7 per cent. shorter, from the bar of worked and stretched wax. The volume of the two pieces of wax remained the same, but the shape of the wax did not.

The only wax of the above tested waxes (see Tables I and II and Fig. 3) that has not a large expansion and contraction is that suggested by the writer for taking impressions for the stone model method of procedure. It also has an exceptionally low proportionate elasticity, about one-tenth of that of carving waxes. The contents of the Price impression wax are pure—

White gum damar,	110 parts
Tamarack (*hackmatack*),	10 "
Beeswax (pure),	15 "
Paraffin,	10 "
Stearic acid,	2 "

—melted together in the order named and kept free from water. It should be used as cool as possible with wet fingers, and only the surface warmed soft when using.

It is not a carving wax, but an impression wax, and is used to take the impressions in which the hard stone models of the cavity are made, and the near tooth surfaces of the same and adjoining teeth, for this model method. Its total volume change from temperature is only from one-quarter to one-half that of the various carving waxes. Its virtue consists in its not introducing much error either from contraction or from elasticity. When an impression is taken with it at its working temperature of 98° F., and is cooled to 67° F., the contraction change is only 0.6 per cent., whereas if the same impression were taken with S. S. White black inlay wax, the contraction would be 2.3 per cent., which error goes forward in each case if the model or pattern is placed in the investment material at that minimum or room temperature of 67° F. Under these conditions the contraction error carried forward by each of the waxes would be as follows: Bird & Moyer, 1.2 per cent.; Cleveland dental inlay, 1.2 per cent.; Klewe, 1.2 per cent.; Consolidated, 1.5 per cent.; Peck, 1.4 per cent.; S. S. White black inlay, 2.3 per cent., and S. S. White crown sticky-wax, 1 per cent.

All of these contraction errors can be controlled by re-heating when investing, if the condition of the wax is not one of internal stress or stretch—in which case the elasticity error, as just shown, may double or triple the expansion error sought, and the ultimate error is very much greater than if the wax pattern were kept cold when investing. The errors or changes due to elasticity of the waxes is never a uniform change, but a true distortion of the mass or part of it. It is probable that every member of the dental profession has experienced a distressing practical example of the contraction change of beeswax when using it for making a bite in order to articulate models when teeth were present in the patient's mouth. He had to either warm it to force it on to the models or carve the wax to let the teeth into it. Even if he warmed it to the temperature which it had when he took the bite, it was often warped.

Up to this point in our procedure, where we have the wax pattern invested, we may have accumulated an error of contraction in the dimension of our cavity pattern, if we invested at room temperature, of from 1 per cent. to 2.3 per cent., according to the inlay wax used; or if we heated when investing, we may have produced an apparent expansion above our starting dimension of from 1.3 per cent. to 2.3 per cent. But, while the volume change takes place regularly with the heating, the expansion does not take place uniformly, owing to the elasticity of the wax, which elasticity is always present when the wax is cooled under a stress. In getting the above ex-

pansion of, say, 2.3 per cent., we may in some part of the wax pattern have a linear distortion change, by releasing the elastic stress, of even 6 or 10 per cent. If we have taken an impression with Price's impression wax and cooled and invested or placed the stone model material in it at room temperature, we have a contraction error to carry forward of 0.6 per cent., or if with the S. S. White crown sticky-wax a contraction error of 1 per cent. Neither of these waxes are suitable for heating very much when investing or when placing the model in them. The former has a very small elasticity error, and the latter a large one, if warmed. In hot weather the temperature of the room is sufficient to release the elastic stress and allow the distortion to take place, though slowly, in all the inlay waxes, especially in the low-melting ones, which, however, have least elasticity.

FACTOR OF ERROR IN THE SETTING OF INVESTMENT MATERIAL.

The next possible source of change in the dimension of our cavity record lies in the setting process of the investment material, but this is not an important factor, as it is small and always represents an expansion. It is as follows—in fractions of 1 per cent.:

Pelton & Crane's inlay investing compound, 0.18; Pelton & Crane and one-half plaster, 0.1; Brophy Imperial, 0.09; Brophy Imperial and one-half plaster, 0.08; Sump, 0.09; Sump and one-half plaster, 0.10; Dendrolite, 0.09; Dendrolite and one-half plaster, 0.05; Fyrite, 0.10; Fyrite and one-half plaster, 0.05; Peck's, 0.07; Peck's and one-half plaster, 0.07; plaster of Paris, stiff mix, 0.13; plaster of Paris, thin mix, 0.10; I. D. L., 0.07; I. D. L. and one-half plaster, 0.8; Taggart's, 0.07; Taggart's and one-half plaster, 0.10.

An error from this source or an opportunity to correct an error from another source is so small as compared with the other errors or changes that we can dismiss the change in the setting of the investment.

FACTOR OF ERROR IN THE EXPANSION OR CONTRACTION OF INVESTMENT MATERIAL ON HEATING.

The next change, however, is very important. It is the expansion or contraction of the investment material when it is heated to burn out the wax, whereby the dimension of the cavity record may be changed considerably according to the procedure employed. In general, all the investing compounds which contain plaster for a binder with silica in excess expand regularly with an increase of temperature up to from 800° to 1000° F., while plaster alone expands only up to 350° F. Above these temperatures these contract rapidly on heating, and all suffer considerable contraction in cooling as compared with either their dimension when heated or before heating. The maximum expansion of the mold from heating, and the subsequent contraction when cold—both in fractions of 1 per cent. for the various investments—is as follows:

Pelton & Crane, maximum expansion 0.71 at 1000° F., contraction on cooling to —0.50; Pelton & Crane and one-half plaster, maximum expansion 0.40 at 350° F., contraction on cooling to 1.10 Brophy Imperial, maximum expansion 0.48 at 900°, contraction on cooling to —1.20; Sump, maximum expansion 0.40 at 310°, contraction on cooling to —1.50; Sump and one-half plaster, maximum expansion 0.35 at 350°, contraction on cooling to 1.40; Dendrolite, maximum expansion 0.35 at 350°, contraction on cooling to —3.50; Dendrolite and one-half plaster, maximum expansion 0.36 at 350°, contraction on cooling to 1.40; Fyrite, maximum expansion 0.38 at 350°, contraction on cooling to —1.20; Fyrite and one-half plaster, maximum expansion 0.34 at 350°, contraction on cooling to —1.50; Peck's, maximum expansion 0.70 at 1000°, contraction on cooling to —0.70; Peck's and one-half plaster, maximum expansion 0.32 at 400°, contraction on cooling to —1.10; plaster of Paris, stiff mix, maximum expansion 0.45 at 350°, contraction on cooling to —1.80; plaster of Paris, thin mix, maximum expansion 0.30 at 300°, contraction on cooling to —2.40; I. D. L., maximum expansion 0.66 at 1000°, contraction on cooling to —0.80; I. D. L. and one-half plaster, maximum expansion 0.35 at 500°, contraction on cooling to —1.50; Tag-

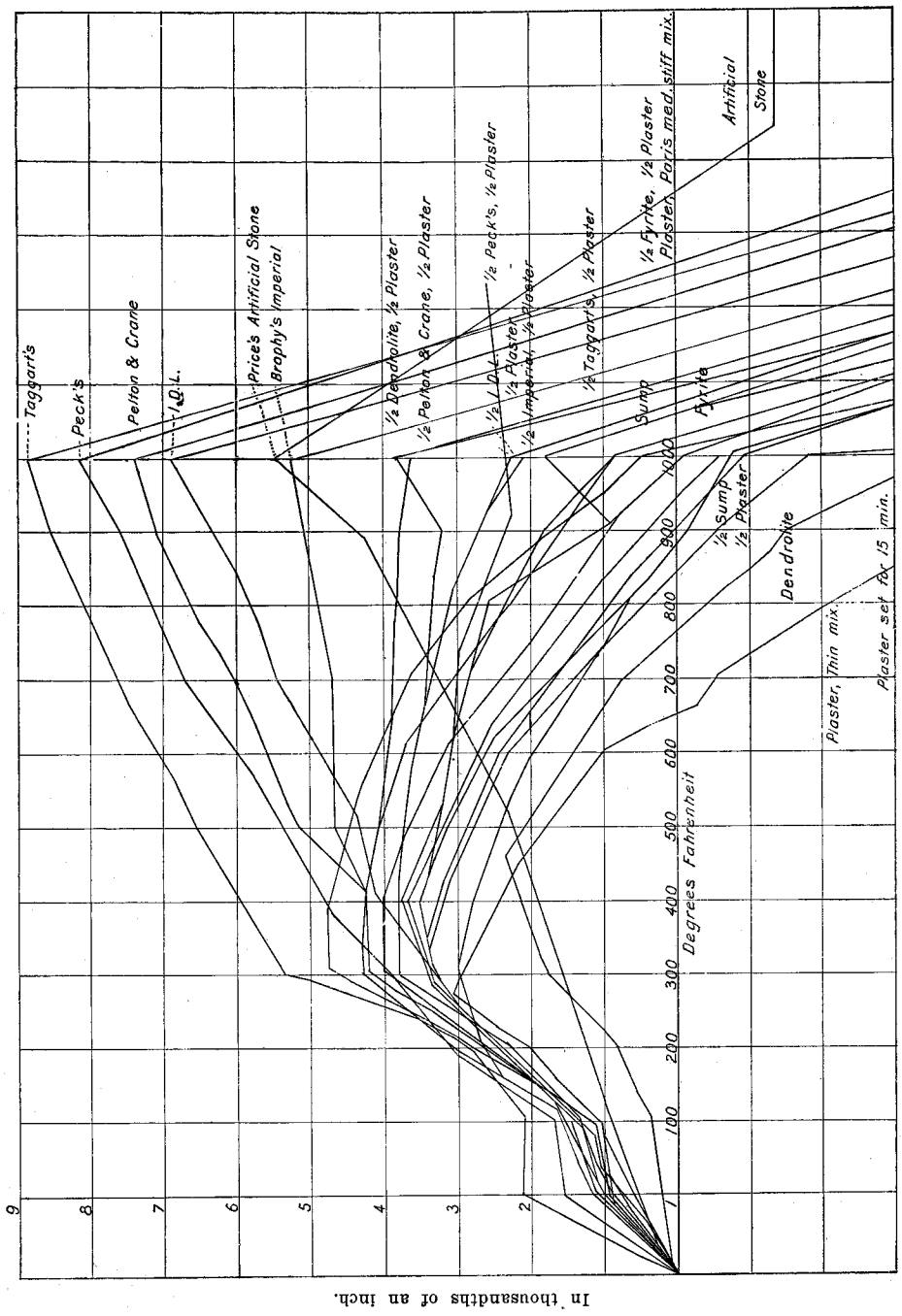


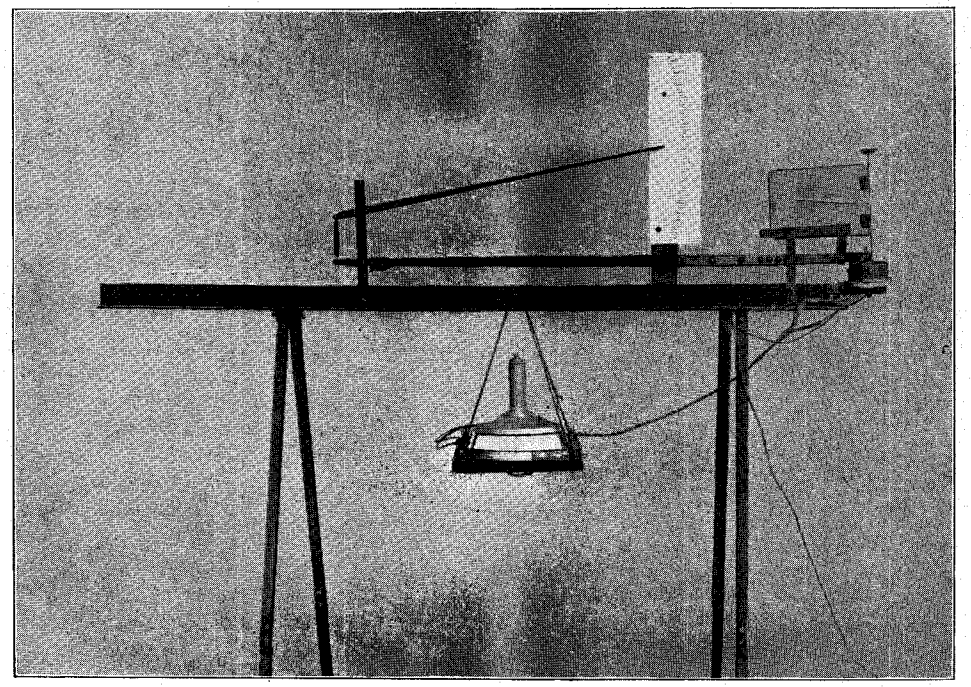
FIG. 5. EXPANSION AND CONTRACTION OF INVESTMENT MATERIALS.

NOTE.—Owing to the size of the original diagram, the lower portion showing the contraction is here omitted. The text, page 276, gives the maximum expansion and the contraction on cooling.

gart's, maximum expansion 0.85 at 1000°, contraction on cooling to —0.60; Taggart's and one-half plaster, maximum expansion 0.34 at 300°, contraction on cooling to —1.10; Price's artificial stone for models, maximum expansion 1.20 at 900°, contraction on cooling to —0.02.

The expansion and contraction of all the above compounds at all temperatures up to 1000° F., and again on cooling, is recorded graphically in the chart of curves of temperature in Fig. 5. The base line shows normal dimension, and the expansion in thousandths of an inch is shown in the elevation above that base line. The temperature is shown as normal at the left, and increases in divisions toward the right. The contraction on cooling is shown by the descending curves to the extreme right. This chart shows at a glance the temperature at which the investments should be cast into, to secure the maximum expansion of the mold, and thereby the amount of correction that can be made to offset some of the unavoidable contraction. It also shows the additional error that can be made by letting the investment cool again after heating, before casting into it. These measurements were mostly made in the apparatus shown in Fig. 6, which was made especially for the study of temperature expansions. The piece being studied is heated in a platinum muffle and the temperature recorded by the pyrometer.

FIG. 6.



Author's expansion recorder, with muffle and pyrometer.

In the selection of the temperature of the investment when casting we can control a range from increasing the size of our cavity record by one per cent. or of decreasing it by two per cent. Our total error to and including this step may range—first, from an accumulated contraction error of 3 or 4 per cent. to a zero dimension without introducing a distortion error from elasticity; second, to an accumulated expansion error of

3 per cent., with elasticity distortion errors.

FACTOR OF ERROR IN THE POSSIBLE CHEMICAL OR PHYSICAL ACTION OF IMPRESSION WAXES UPON THE INVESTMENT MATERIAL.

The next possible error will arise from the chemical or physical action of the impression waxes upon the investment material. This is not a source of much error, and, when it does occur, is a distortion of the mold from flaking of the surface. It usually occurs only when the wax is burned out after the investment has been allowed to dry out. A moist investment when heated will protect the surface from the wax by the steam forcing the wax out of the surface of the mold, instead of melting it into the surface. The error from this source would be a distortion, and not a uniform change in the cavity dimension.

FACTOR OF ERROR IN THE PRESSURE OF THE MOLTEN GOLD UPON THE INVESTMENT.

The next error arises from the pressure of the molten gold upon the investment; this is considerable in amount if the investment is soft owing to either an excess of silica, or poor plaster, or very thin mix, or to heating too soon after mixing and before the plaster has become strong, also to a high pressure. The strength of the investing material when it is entirely cold is much greater than when hot, which gives to readings on cold specimens only a relative and approximal value. Fig. 7 shows graphically the effect of pressure on a cold cubic block, one inch square, of the various investing compounds set under conditions ideal for maximum strength. It indicates chiefly their relative resistance, since the conditions for this test were not those under which we use them practically. The measurements were made with an end comparator made by the Société Geneviève, Switzerland.

The pressure was produced by a smooth flat round surface about one-eighth of an inch across, and 1/91 of a square inch of surface. The curves of Fig. 7 show the distance, in thousandths of an inch, that the plunger penetrated the cold blocks at the various pressures at which some of the blocks collapsed. For example, with the Pelton & Crane cold investment, 16-oz. pressure on a surface 1/91 of a square inch produced an indentation 14/1000 of an inch deep, and at this pressure the cube collapsed. Silica and plaster, four to one, broke at 37 oz., and at that pressure had yielded over 40 thousandths. Taggart's broke at 37 oz., and had only distorted or yielded 5 thousandths. The majority did not crush at 58 oz., and their exact yielding at that pressure is shown on this chart. The artificial stone suggested by the writer did not indent, and was crushed only at a pressure of 16,000 lb. per square inch. Table III shows in detail the amount of indentation into the cold blocks at the pressures indicated.

For demonstrating how easily the investment will fracture when not supported, the following is interesting: A large investment ring is filled even with investment around a small spiral wax core attached to a glass tube with a flange to hold it in the investment, and the wax is burned out in the ordinary way. The cavity is filled with mercury till it shows in the glass tube, by applying air pressure through a rubber tube placed over the glass tube. The bursting force from the pressure of the mercury within will be sufficient to force the investment, if there are no ends in the ring, out of the top and bottom of the ring, with even so low a pressure as 20 lb. per square inch. In this case the conditions are not identical or similar to those when air pressure is used in casting, in which case it is applied to the top of the investment as well as to the metal column going within. The coefficient of expansion of all investments when heated is several hundred degrees less than that of the metal rings, which latter consequently cannot support and sustain the investment closely, and this readily allows of a slight fracture and distortion. One means to measure the distortion is to cast simul-

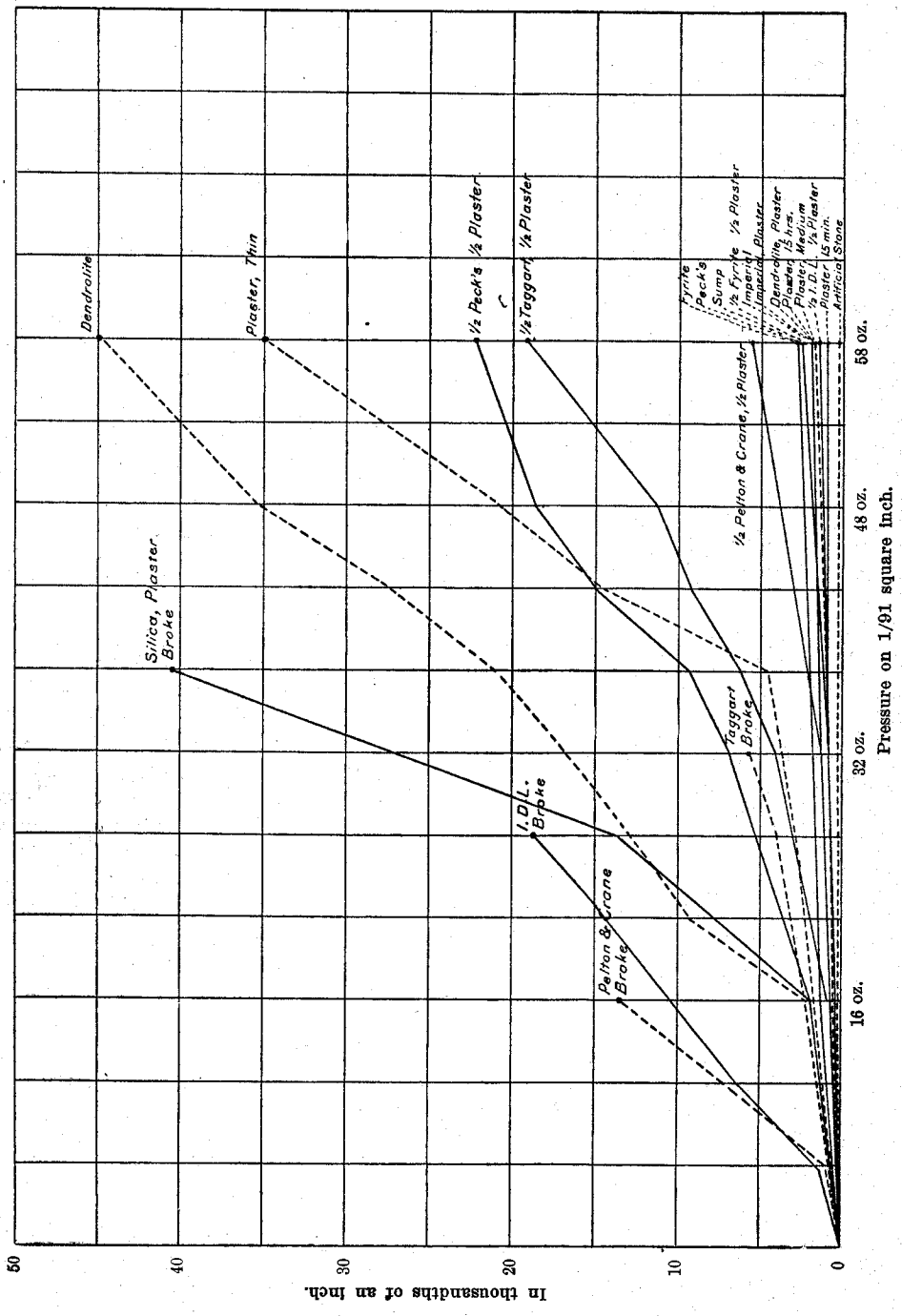


FIG. 7. YIELDING OF INVESTMENT MATERIALS UNDER STEADY PRESSURE.

TABLE III.

YIELDING OF INVESTMENTS UNDER STEADY PRESSURE. ($1.0 = \frac{1}{1000}$ INCH.)

PRESSURE.		Pelton & Crane.	½ P. & C. ½ Plaster.	Imperial.	½ Imperial. ½ Plaster	Sump.	½ Sump. ½ Plaster.	Dendrolite.	½ Dendrolite. ½ Plaster.	Fyrite.	½ Fyrite. ½ Plaster.	Peck's.	½ Peck's. ½ Plaster.	Plaster, medium.	Plaster, thin.	I. D. L.	½ I. D. L. ½ Plaster.	Taggart's.	½ Taggart's. ½ Plaster	Plaster, set 15 min.	Plaster. set 15 hrs.	½ Silica. ½ Plaster.
Lb. per sq. inch.	Oz. on surface 0.127 inch diameter.																					
16	*oz.*																					
0	0.	0.	0.	0.	0.	0.		0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
. . .	5.3	1.0	. . .	. . .	. . .	. . .		0.4	. . .	. . .	. . .	. . .	. . .	. . .	0.2	1.4	. . .	. . .	. . .	. . .	. . .	0.4
. . .	10.7	7.0	. . .	. . .	. . .	. . .		1.2	. . .	. . .	. . .	. . .	. . .	. . .	1.0	6.3	. . .	. . .	. . .	. . .	. . .	1.2
91	16.	13.6	0.6	0.7	0.7	0.4		2.2	0.8	1.2	0.6	0.5	2.0	0.7	1.8	10.5	0.4	. . .	0.8	0.2	0.6	2.0
. . .	21.	Broke	. . .	. . .	. . .	. . .		9.3	. . .	. . .	. . .	. . .	. . .	. . .	2.4	14.3	. . .	. . .	. . .	. . .	. . .	8.0
. . .	27.	. . .	. . .	. . .	. . .	. . .		12.8	. . .	. . .	. . .	. . .	4.5	. . .	2.8	18.7	. . .	2.0	2.0	. . .	. . .	18.5
182	32.	. . .	1.3	1.2	1.3	1.3	(No sample.)	16.6	1.2	1.7	1.3	1.1	6.9	1.1	3.7	Broke	0.7	5.9	4.0	0.5	1.2	28.0
. . .	37.	. . .	. . .	. . .	. . .	. . .		21.3	. . .	. . .	. . .	. . .	9.3	. . .	4.6	. . .	. . .	Broke	6.3	. . .	. . .	40.5
. . .	42.	. . .	. . .	. . .	. . .	. . .		27.5	. . .	. . .	. . .	. . .	15.0	. . .	14.8	. . .	. . .	. . .	9.1	. . .	. . .	Broke
273	48.	. . .	. . .	. . .	. . .	. . .		35.5	. . .	. . .	. . .	. . .	18.8	. . .	20.8	. . .	. . .	. . .	11.4	. . .	. . .	. . .
329	58.	. . .	5.7	2.1	2.0	2.4		45.0	2.0	2.8	2.4	2.5	22.3	1.9	35.0	. . .	1.2	. . .	19.3	1.0	2.0	. . .

Broke—

Pelton & Crane, under less than 21 oz. pressure.
I. D. L., " " " 32 " "
Taggart's, " " " 37 " "
Silica and plaster, " " " 42 " "

Large yielding—

Dendrolite . . . . . 45.
Peck and plaster . . . . . 22.
Thin plaster . . . . . 35.
Taggart and plaster . . . . . 19.

"Artificial Stone."

Under pressure of 58 oz. (= 329 lb. per sq. in.).
Compression of 0.5 ($\frac{5}{10000}$ inch).
True elasticity; no indentation produced.
Specimen broke at 175 lb. = 16,000 lb. per sq. in.

taneously a bar and a ring attached to the same sprue gate, the wax pattern for which must be made from wax that has been entirely relaxed to remove its elasticity by warming several times nearly to its melting-point before finally carving. The bar of wax is made of a known length, and the ring is made to go over the base of a taper column. In each case the change in dimension for temperature change will be the same, and can be easily determined from the data here given. In fact, all the changes that affect the dimensions will be the same for the two pieces except that the distortion changes of the investment from pressure that will affect the measurements will appear on the ends of the bar and on the inside of the ring. In the former the error will make it appear larger, and in the latter smaller. This is not a uniform change of expansion, but an uneven distortion. The possible or probable errors from this source are so great as to cause a low pressure to be generally used with a soft, weak investment, and make it essential that a hard model or hard investment be used to cast into when a very high pressure is applied. The surface errors due to beads of air or organic matter in the investment should be classed as distortion errors of the surface, and amount generally to a few thousandths at least. Any of these sources of distortion—the compression of the soft investment, the checking and bursting of the mold, enlarging it, or the surface defects of the mold under pressure—may prevent an otherwise very accurate reproduction from going to place or fitting, and will usually be erroneously classed as a uniform expansion, even when they accompany an actual contraction. The first two of these forms of distortion are practically eliminated entirely from all cavity surfaces when casting into a hard stone model or any similar hard mold, and trouble with the latter form is very greatly reduced.

It is impracticable to try to express distortion errors as per cent. increase or decrease in the size of the cavity record, but they usually mean a large increase at some single diameter or surface, making it impossible for an inlay to fit closely to all surfaces within even several thousandths or probably several hundredths of an inch.

ACTION OF THE MOLTEN GOLD ON THE INVESTMENT.

The action of the molten gold on the investment is not a source of large error in the more recent investments which contain a large percentage of silica, but it was so in some of the early compounds which contained fusible ingredients, as soda glass. In their fusing in the surface of the mold or chamber, this was enlarged or distorted.

CONTRACTION OF THE GOLD IN COOLING.

The universally large and fixed error that is a part of all the methods of technique, and the one step around which all others hinge, is the casting of the gold and the contraction continually attending its cooling to normal temperature. This error is divided into the change of dimension attending the change of the physical state from liquid to solid (corresponding, though in a different direction, to the change occurring when ice is formed—having an 11 per cent. greater volume than water) and the contraction from the freezing-point of the gold to normal temperature.

This is the first publication, as far as the writer knows, of any data relating either to the fact of such change of volume with change of state, or its nature and amount. While it is not an exceedingly difficult matter to determine the change in dimension from the frozen or crystallized state down to normal temperature, it has been an exceedingly difficult matter to determine quite accurately the volume change attending that physical change. During the winter of 1907 and 1908 the writer determined the linear contraction change of the gold from its crystallizing or freezing point to normal or room temperature (as published in *Items of Interest,* May 1908), and found it to be 22.5 thousandths, or 2.25 per cent.; but, as stated, these determinations could only be carried to and

from the temperature where the gold bars still had considerable strength, and did not include any of the change of dimension with change of state, or the changes occurring close to the crystallizing temperature. Fig. 6 shows the instrument used. Quite continuously since that time the writer has carried on investigations to determine just what occurs when gold crystallizes. One of the methods chiefly used to determine the total contraction of gold after freezing consisted in casting into fused quartz chambers of known dimension, and directly measuring the contraction. This present review of the errors so far encountered in the technique of casting, viz, those of the wax and investments, explain fully the necessity for eliminating all the foregoing technique for a quantitative determination, because the errors introduced would require difficult and uncertain corrections to be made. It becomes necessary to use as a substance for measuring and casting gold into, one with a minimum of expansion and contraction, and the temperature ratio of such change must be a known quantity. Fused quartz has the most favorable qualities of any substance available, since its dimensional change with temperature is about one-fortieth that of gold, and its rate of change is known with accuracy. For this determination it was desired to measure the volume of the gold in the molten state, and again in the cold state, and also at the same time, if possible, to measure the effect of pressure on the location of the contraction as the column was crystallizing, the pressure at any point being equal to the weight of metal above it.

DELICATE TESTS FOR ACCURATELY MEASURING THE CONTRACTION OF GOLD.

Since gold is approximately 19.27 times heavier than water, a column of molten gold a foot and a half high would have a pressure at the bottom equal to atmospheric pressure, or equal to a column of water 30 feet high. By letting a column of molten gold of known height and diameter crystallize under its own weight, the total reduction in volume would of course be the difference between the volume of the molten column and the same column when cold. The contraction of the cooling column after crystallizing being measurable, the difference would be the change due to the change of state. The effect of pressure on the cooling mass would be exactly indicated by the relative reduction in the cross section at any point, as the mass cooled under its own weight, if the molten column had parallel sides of known distance apart. To accomplish this determination, the writer had made of fused quartz a chamber, 25 cm. (10 in.) high, and 1 cm. wide and 2 mm. across. This chamber was made by placing four pieces of fused quartz together, two narrow pieces, 3 cm. wide, being placed 1 cm. apart, between two pieces 7 cm. wide. The two inner edges of the two narrow pieces were ground very straight from end to end, approximately to within one ten-thousandth of an inch, in order to measure accurately the exact reduction in cross section of the gold column at all distances from the top of the column, or at all pressures up to the maximum. The lower end of the chamber was closed and the upper surfaces were ground flat and smooth in order to place a flat cap over the chamber to produce a column of molten gold that precisely filled the chamber. A special very large electric muffle was constructed to receive and heat the quartz vessel. It was necessary to have the quartz blocks made in Germany—which, together with the labor expended in making the two straight edges so accurate, made the instrument very expensive. Since fused quartz has a lower expansion and contraction change with temperature than any substance that could be found to hold it together, it became impossible to hold the quartz pieces together at the high temperature of molten gold under the enormous pressure of the full ten-inch column of molten gold, which was equivalent to a column of water twenty feet high. A four-inch column was the highest that could be sustained, which gave us measurable cross sections up to that pressure to de-

termine the effect of pressure on the location of the contraction. The chamber of fused quartz was then made in the form of a continuous tube with the lower end closed and the upper end ground flat as before. This permitted only of the determination of the entire change of volume from liquid to normal temperature, without the possibility of measuring at the same time the effect of pressure on the location of the contraction. A special platinum wire resistance muffle furnace was again made to heat this one-piece quartz chamber filled with gold. A pyrometer thermo-electric couple was placed at the base of the chamber to record its temperature. When the chamber was slightly more than full of molten gold the ground-flat cover made of artificial stone and heated was placed over the chamber and pressed down, thus crowding off the excess as the temperature was held at just the melting-point by means of the pyrometer and rheostat. This was repeated five times, and the gold was weighed with great exactness as will be explained. This determination of the volume change of the gold is based on measuring the difference in the volume change of the fused quartz and the gold, and thus determining the volume change of the gold, that of the fused quartz being known. Fortunately, this latter change has been determined very accurately by Mr. Howard Minchian of the department of physics of the University of Michigan, to within an error of one part in 1,500,000, by the following method: A beam of monochromic light was passed through a fused quartz piece supported on a fused quartz cylinder to be measured, in such a way as to produce interference rings, and, as the cylinder expanded on being heated, the rings moved outward with each additional wave-length of distance between the reflecting surfaces. In other words, the divisions of the ruler used for measuring were the waves of light themselves. Mr. Minchian found the coefficient of linear expansion (the rate of expansion per degree) of fused quartz constant up to 950° C. and to be $44.9 \times 10^{-8} = 0.000000449$. Cubical or volume expansion is approximately three times linear expansion. The volume of the fused quartz chamber was determined by weighing the mercury which it contained, and making corrections for temperature and buoyancy of the air, etc., and measuring the specific weight of the mercury used. Three calibrations gave the volume of the fused quartz chamber at 0° C. to be 3.679 cubic centimeters, and, at the melting-point of gold, 1064° C., this amount plus the cubical or volume expansion of the fused quartz cylinder to that temperature, which, using Minchian's values for the quartz expansion is $[(1 + 3 \times 0.000000449) \times 1064] = 3.686$ ccm.

To reduce the weight of the cold gold which filled the chamber when molten, to volume, its specific weight was accurately determined by weighing in water in the balance shown in Fig. 2, and found to be 19.267 at 0° C. The weight of the cold gold which filled the chamber when molten was determined by five tests, and found to be 63.670 grains, which reduced to cubic centimeters is $63.670 \div 19.267 = 3.305$.

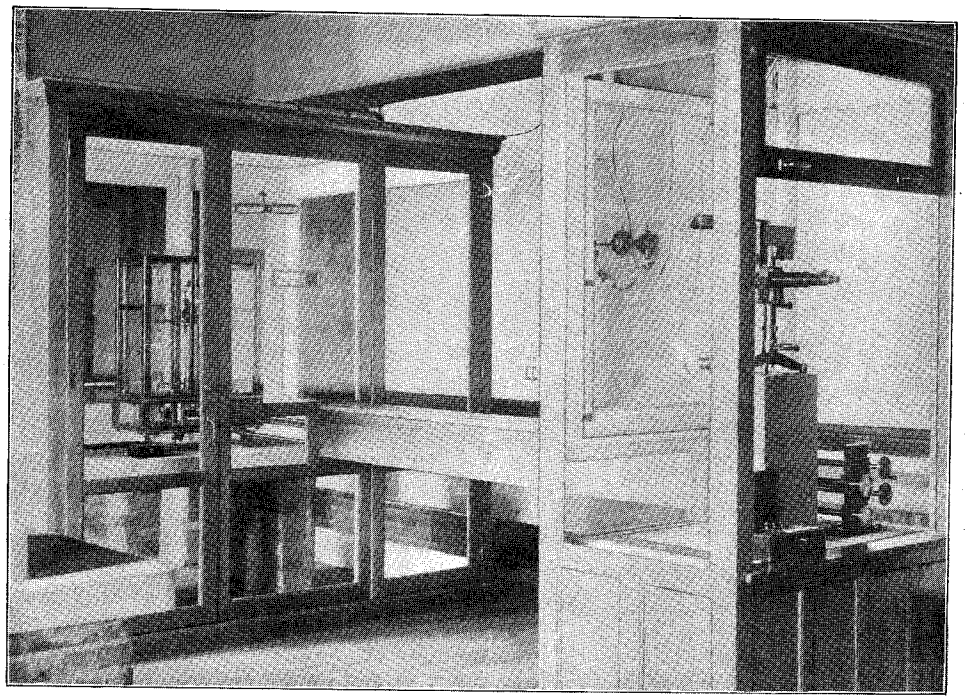
The weighing of the gold and the mercury required to be done with very great accuracy, and it was done with the instrument shown in Fig. 8, which is credited with being the most sensitive weighing instrument on the continent. It will register, for example, the difference in the weight of a kilogram weight when lifted two inches farther from the earth. It is a part of the splendid equipment in physics at the Case School of Applied Science. The weighing is done at a distance of twelve feet from the balance and in a separate cabinet, the weights being operated by a mechanism extending into the double case surrounding the balance. The readings are made with a telescope. It takes about two hours to make a single weighing, which can be done to within one thirteen-thousandth part of a grain on a full load of two and one-half pounds.

The volume of the gold at 0° C. was 3.305 ccm., and when molten at 1064° C., 3.686 ccm., hence its total contraction between these temperatures is 0.381 ccm. The contraction per cubic centi-

meter is 0.381 ÷ 3.305 = 0.1153, or, expressed in per cent., the volume change or total contraction is 11.53, which is probably much larger than any of us suspected. Since linear change is one-third the volume or cubical change, the total linear contraction of gold is 3.84 per cent. from the molten state to 0° C.

16.201 cm. or seven inches long and one-quarter of an inch in diameter. A special platinum wire resistance muffle was made for each, closely fitting to the gold, and with a thermo-electric couple attached to the bar in the center of the muffle, and insulated from the gold as it passed out. The square ends of the

FIG. 8.



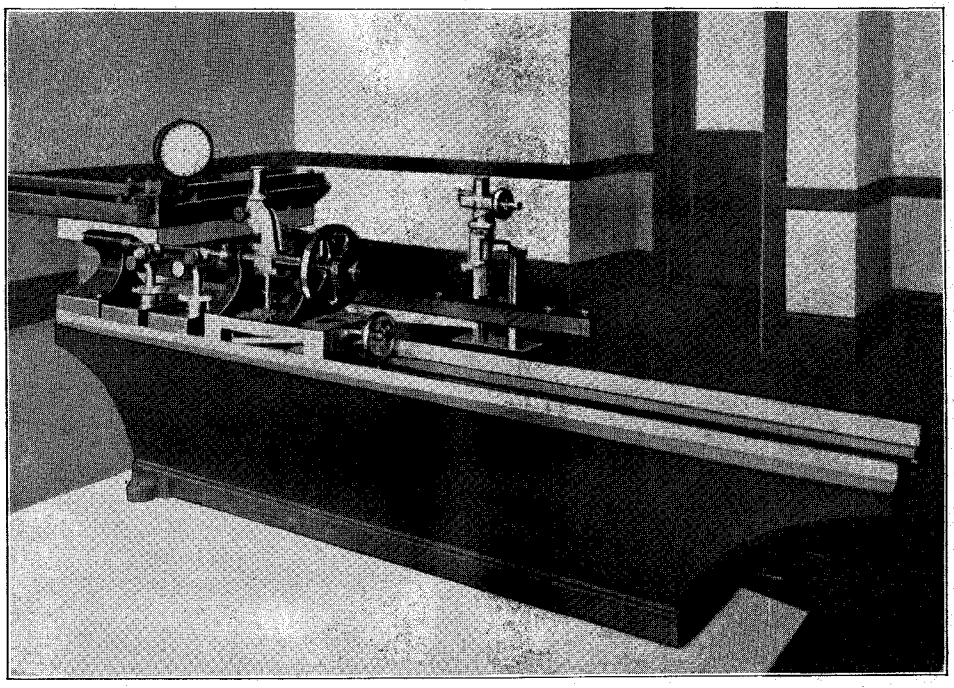
Large precision balance. General view, showing operation from a distance.

To find the part of this change that is due to change of state we must subtract that part which takes place after the gold has crystallized.

The writer had previously determined this to be, as noted, 2.25 per cent. linear or 6.75 per cent. volume. To verify or correct these measurements they were repeated with great care to eliminate all possible sources of error such as radiation. Two bars of the same gold were made of different length, one 12.619 cm. or about five inches long, and one-quarter of an inch in diameter, and the other bar were covered with measured mica plates to reduce radiation at that point. The bar was heated slowly, and measurements were made on the ends, at every 50° C. up to the sagging point. These measurements were made very accurately in an end comparator measuring to 1/100,000 in. The instrument is shown in Fig. 9. But there was some radiation at the ends of the bar, which error must be eliminated. Since any two similar bars have the same error from radiation at the exposed ends, a section in the center of the longer bar, left after

subtracting the shorter bar, will represent the true expansion, since all errors from radiation have been removed by subtracting the shorter bar. Hence the two-inch section in the center of the seven-inch bar left after subtracting the five-inch bar will be free from radiation errors. These measurements are shown graphically for both bars in Fig. 10. The base line represents temperature, and the elevation shows expansion in hundredths of a centimeter. Since the gold has not strength within fifty degrees of its melting-point, that part of the curve had to be computed, and is shown extended in the dotted line in Fig. 11. In this chart is given the expansion of a bar, 1 cm. long, in thousandths of a centimeter. The base line represents temperature, and the elevation expansion. The lower curve is the expansion of a 1-cm. piece from the longer or seven-inch (16 cm.) bar, without correcting for end radiation, the upper the expansion of the same piece after eliminating end radiation, and the dotted part the extension for the part of the range too near the melting-point for the gold to have strength enough to measure, so is computed. In this chart the curve of expansion for the fused quartz is also shown up to the same temperature, viz, the melting-point of the gold, and, as seen, it is very small in comparison.

FIG. 9.



Precision end comparator, used in measuring length of gold bar.

These more exact measurements of the expansion of pure gold up to its melting-point change the second decimal of the original determinations, making it 2.20 per cent. linear instead of 2.25 per cent., and 6.60 per cent. volume instead of 6.75 per cent. This contraction of the gold after crystallizing or freezing, subtracted from the total contraction, gives the contraction that takes place with the change of its physical state—viz, expressed as volume or cubical

FIG. 10. OBSERVED EXPANSION OF GOLD BARS.

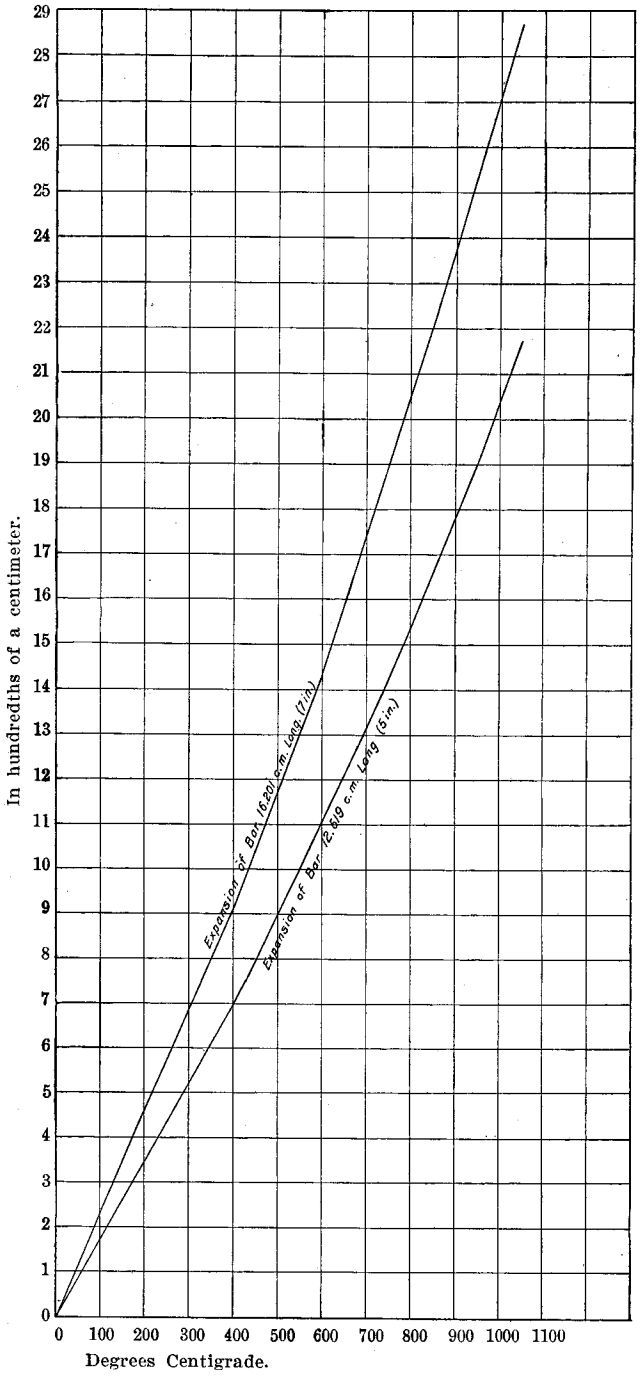
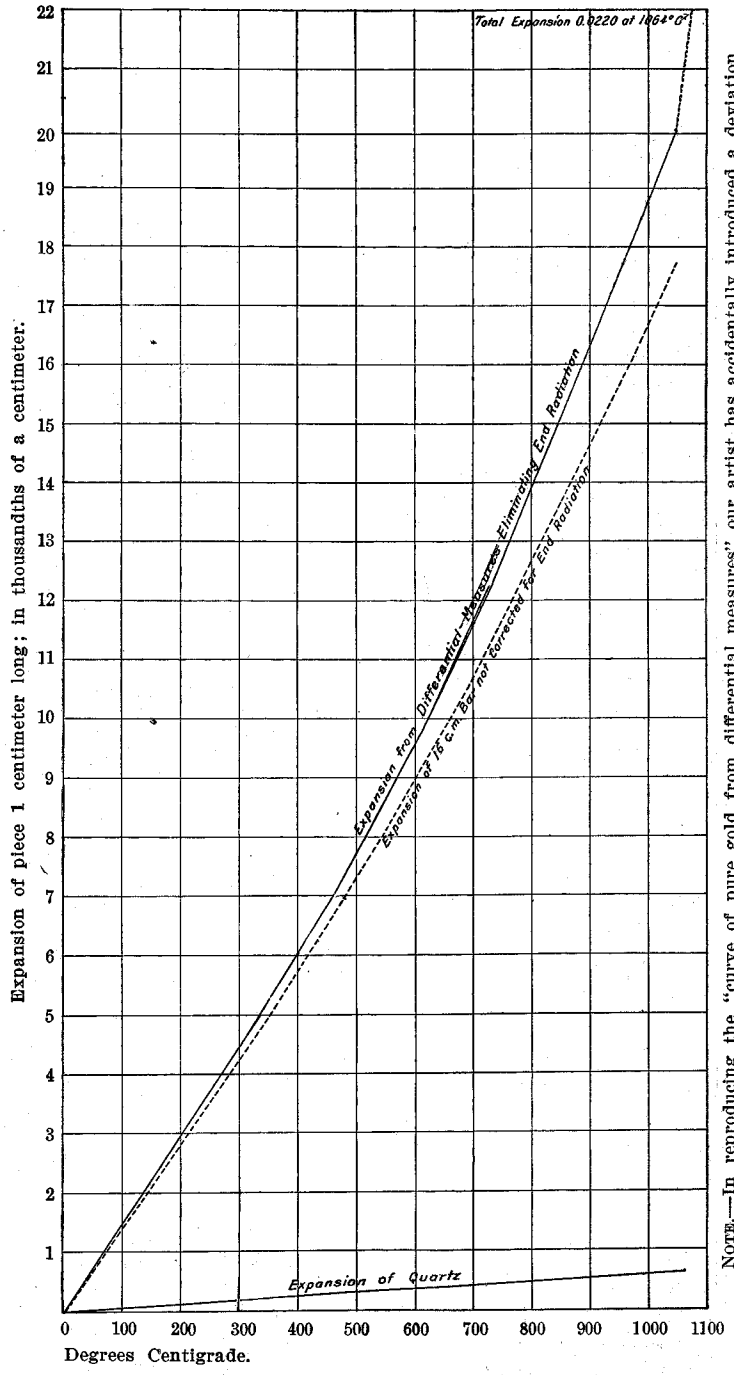


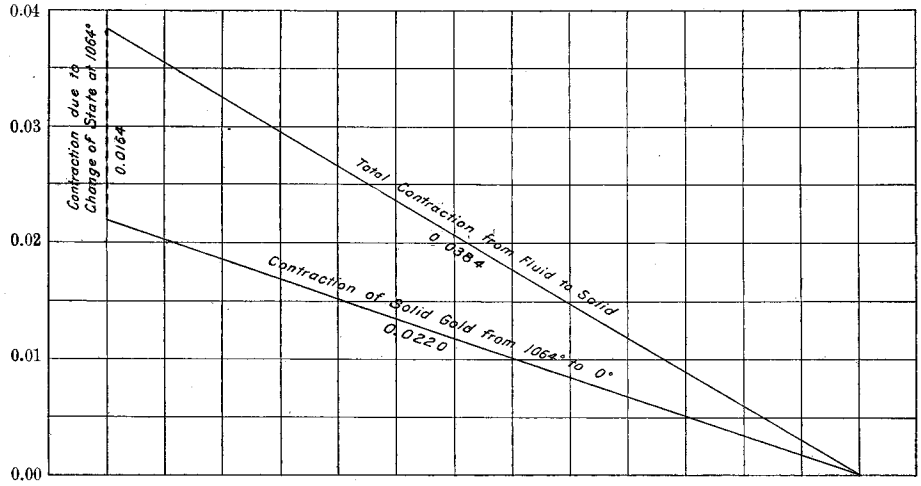
FIG. 11. LINEAR EXPANSION OF PURE GOLD, AND EXPANSION OF QUARTZ.



NOTE.—In reproducing the "curve of pure gold from differential measures" our artist has accidentally introduced a deviation of the curve, beginning from about 800 degrees and 14 thousandths upward, and at the 20-thousandth expansion abscissa has drawn an angle in order to finish the line at the correct point. This is an error of delineation that apparently invalidates the law of expansion, which is properly represented by a curved line. This curved line is correctly drawn in the author's copy and does not form an angle at the point indicated, but continues as a gradual curve through the 20-thousandth expansion abscissa slightly to the right of the 1000-degree ordinate, thence onward to the terminal total expansion point. This error was discovered too late for correction of the diagram before going to press.—ED. COSMOS.

change, 11.53 — 6.60 = 4.93 per cent., due to change of state or latent heat of fusion; or, expressed as linear contraction, 3.84 — 2.20 = 1.64 per cent., or linear contraction due to change of state without change of temperature. Fig. 12 shows graphically the proportion of the contraction changes. It may be assumed that, wherever and whenever pure gold is melted and cooled, these changes in dimension take place, and this becomes one of the most rigidly fixed factors to control its location. In other words, we can, by forcing in molten gold from the sprue to take the place of the accumulated contraction in the inlay, cause all the contraction due to change of state to appear in the sprue. This can only be done by having the gold in the sprue molten when that in the inlay is crystallized, which can best be secured by having the mass of gold in the sprue large in proportion to the inlay, and by using a high enough pressure to move the gold

FIG. 12. TOTAL CONTRACTION OF GOLD.



which we must adapt our technique. In other words, we must systematically produce a definite error elsewhere to neutralize or correct that part of this error that cannot be controlled.

CONTROL OF THE LOCATION OF THE CONTRACTION OF GOLD.

Probably no dentist who has done casting has failed to see that frequently there was a hole or depression in the side of the casting, or even a complete separation between the sprue and inlay. This is the result or expression of the contraction due to change of state; it is, however, an error that we can control entirely. While we cannot prevent contraction due to change of state, we can in; also by using a relatively large gate, and having the investment sufficiently heated so that the gold will not be quickly chilled in the gate. With a high pressure not only can this part of the contraction—*i.e.* that due to the change of state from liquid to solid, and amounting to 4.9 per cent. of volume and 1.64 per cent. of linear dimension—be entirely controlled, but, if conditions are made favorable as by the above suggestions, even a little more of the contraction than the above can be controlled by pressure, for as long as the pressure on the column of gold is greater than the strength of the gold, the latter will move. Fig. 13 is a chart showing graphically the effect of pressure on gold and its alloys after they have passed through the change

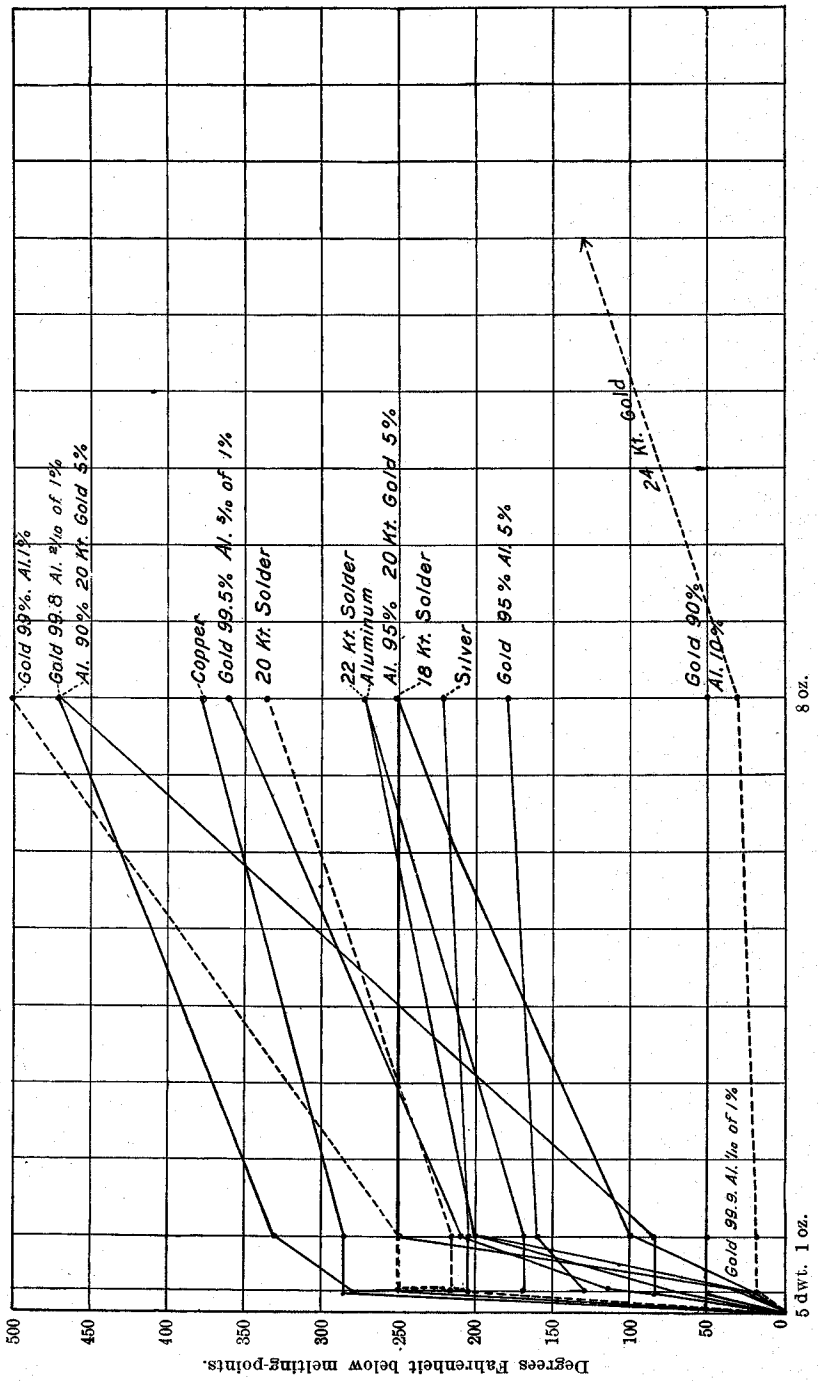


FIG. 13. PRESSURE MOVEMENT OF GOLD AND ALLOYS AFTER CRYSTALLIZING.

of state and are crystallizing and cooling toward zero.

CONTROLLING THE GOLD BY ADDING ALUMINUM.

Eight ounces of positive pressure, on a square surface one-eighth of an inch square, moves pure gold, as shown by this chart of curves of pressure effects, only 30° F. below its melting-point, and if 0.2 per cent. of aluminum be added to it, the strength of the crystal is so reduced that it will move 470° F. below its melting- or freezing-point. Pressure of 24 oz. on the same surface will move pure gold 200° F. below its melting-point. It will be obvious that these pressures could only be used in practical work when casting into or against a very strong material, if it is to retain the cavity surfaces without distortion. Through the range of cooling temperature below the point where the pressure used will move the congealing mass, the normal contraction will take place, and with pure gold and with the pressure that could be safely used with ordinary investments we cannot expect to do much more than control the contraction due to change of state, though with a hard, strong investment, as when casting into a stone model, we can control a little more. This leaves in general 2.2 per cent. as a fixed contraction error that cannot be prevented in an ordinary technique, and this error must be corrected for by introducing systematically an expansion error elsewhere sufficient to take care of it, or we must mechanically prepare our cavity with a bevel everywhere and depend upon burnishing a pliable metal tightly to that margin. This latter method, however, only provides a correction for the difficulties arising from the shortening or drawing away of the gold from a margin of an inside dimension; it does not relieve those difficulties arising from the shortening of an outside dimension, as when the metal goes over any outside surface, like a double compound cavity or a crown base—where, instead of the contraction drawing the metal away from a margin or surface, it draws it toward it.

CONTROLLING THE GOLD BY CASTING INTO A MODEL OF ARTIFICIAL STONE.

Fortunately we have a means for correcting a large part of this most troublesome class of error—viz, by holding the contracting gold so rigidly that it is compelled to stretch. This is accomplished by making the mold into which we cast of a material so strong that the cooling gold cannot crush it, but will itself be stretched. The practical material for casting into, that has strength enough for this, is a hard model made of a special silicate cement, viz, the artificial stone suggested by the writer, which is made synthetically by fusing together

Pure silica,	20 parts
Calcium hydrate,	19 "
Aluminum oxid,	42 "

at a temperature of about 2750° F. This is powdered free from iron and added to equal parts of a very highly vitrified potshell, and after thorough mixing and grinding together forms a very hard model when mixed with phosphoric acid. The model becomes hard only after being heated with dry heat. Great care is required to have the materials so balanced chemically as to produce a model with zero contraction on setting. It can also be made by fusing together

Kaolin,	3 parts by weight
Calcium hydrate,	1 part " "
Aluminum oxid,	1 " " "

and treating as above.

When inlays for double compound cavities are cast of pure gold on such a model, the gold will be stretched and held. Incidentally this model method has many advantages, as described in detail in *Items of Interest,* September 1909.

CONTROLLING THE GOLD BY CASTING OVER THREADED IRIDIO-PLATINUM BARS.

Another method for holding the gold from contracting, or of causing it to stretch when contracting, is to cast it over iridio-platinum bars that have been threaded. This will control a large part of it, if the proportion of iridio-platinum to pure gold is large, otherwise the bar itself will be contracted. If the bar is

not in the center of the mass, the whole will be warped by the uneven contraction. These bars answer a double purpose in inlays by giving a greatly increased strength just where most needed. They should be used in double compound cavities when united through a shallow or narrow step in the occlusal surface, and in the occlusal step of approximal cavities. This method of preventing the normal contraction of the gold by iridio-platinum bars will not, however, correct more than one-half of the normal contraction, depending upon the relation of the masses of each, iridio-platinum bar and pure gold, and the shape of the casting. We can count ordinarily upon one-half of 1 per cent. correction from this source in the occlusal step of single or double compound cavities.

The relatively exact changes of dimensions that we have been reviewing as accompanying the technique chiefly of the Taggart direct method are all common to most inlay methods to a greater or less extent, and the one process which is common to all and is the foundation of them all, viz, the melting and cooling of gold, obeys the same laws in all methods. This is the one fixed condition to which all our technique must be adjusted, and it may be briefly stated as follows: Gold when molten occupies approximately one-ninth more space than when at normal temperature, and just after changing its state, or freezing, occupies approximately one-fifteenth more space than at normal temperature.

The gold can be moved, when changing its state, by pressure which enables us to determine or control the location of the displacement due to change of state. The location of the remaining part of the change of dimension or contraction can only be controlled in small part by pressure, unless a very high pressure be used and unless a small per cent. of aluminum be added to the gold to change its law of crystallization.*

* The writer, before differentiating between the contraction due to change of state and that due to the contracting solid gold, read pressure control as all being over the contracting solid gold.

The contraction after crystallization, of 2.2 per cent. linear or 6.6 per cent. volume can only be corrected by compensation—that is, by uniformly enlarging the mold which is to receive it.

RÉSUMÉ OF DIMENSION CHANGES AS PRODUCED BY EACH STEP IN OUR CASTING TECHNIQUE.

If we now follow through our technique and sum up the dimension changes that can be produced by each step to reduce or add to this fixed contraction, we find—assuming that the contraction due to change of state is controlled by pressure—the following:

First step. In removing the pattern from the cavity we chill it, and thus reduce its volume from 1.8 to 10 per cent., which is a linear contraction of 0.6 to 2.3 per cent. (see Table II), the volume or cubical contraction being three times the linear, making our contraction error, together with that of the gold of 2.2 per cent., total 2.8 to 4 per cent. This provides that the pattern be invested at its reduced temperature, at about 67° F.

Second step. If the wax pattern be warmed when invested, to the temperature at which it was when placed in the cavity, this total contraction error can be reduced to that of the gold, of 2.2 per cent., and if heated to a higher temperature than when it was placed in the cavity we may get an expansion of the pattern above its original size of from 1.3 to 2.4 per cent., or apparently enough to correct the fixed error of the gold. But we have no wax that has so little elasticity as to keep its form when warmed even to the original temperature at which it was placed in the cavity, let alone permitting a higher one; for by heating a molded or stretched pattern of any of the waxes on the market known to the writer we may introduce distortion errors several times worse than the error to be corrected. (See Table II and Fig. 4.) We are compelled for safety, then, until we get a better wax, to invest at the lowest temperature and proceed with an accumulated error

of 2.8 to 4.6 per cent. (the contraction of both the wax and the gold), according to the pattern wax used.

Fourth step. We may ignore the change in dimension of the investment in the process of setting, and pass to that due to heating and cooling the investment.

Fifth step. (See Fig. 5.) This step of heating the investment will give us a choice, according to the technique employed, of an expansion of about 1 per cent. or anything less, to a contraction of 2 per cent., if, after heating a thin mix with an excess of plaster, we let it cool off and become cold before casting. If we cast at the best temperature for maximum expansion (see Fig. 5) our total error will at this point represent a contraction of from 0.8 to 3.6 or even to 6.6, if the investment used has contracted instead of expanding.

We will pass the *sixth step,* viz, the effect of the wax on the investing material, as it is not an important source of error.

Seventh step. The pressure of the gold in the investment material will always produce a serious distortion error if the investment material is very weak and the pressure high. It will appear in the form of distortions, and not as uniform expansion. It is overcome entirely on the cavity surfaces of the inlay by casting into a hard model in the investment.

Eighth step. The action of the gold on the investment we can pass, as being but slight.

Ninth step. The change of dimension due to change of state will be corrected for by pressure; it would not appear as a uniform contraction, but as a fault in the side of the inlay.

Tenth step. The contraction of the solidified gold has already been included as a fixed contraction of 2.2 per cent.

Eleventh step. The distortion of the mold of the cooling gold includes all conditions under which the gold surrounds some investment which is not strong enough to hold its shape as the gold contracts, permitting distortions such as the crushing of the core in a crown base or between the mesial and distal pulpal walls of a double compound inlay. In result, this error is the contraction of the solid gold. Its correction comes in the next step.

Twelfth step. The holding of the gold, causing it to stretch, is done over a hard model or over iridio-platinum bars in its mass, which will permit us to control nearly all of the error due to shortening of the outside dimension of the mass of the gold, if it is not too large in proportion to the mass of the artificial stone or other hard model inside it. But this will only apply to the gold surrounding a core, as the mesio-distal diameter of the mass of gold between a mesial and distal filling in a double compound cavity where these cavities are united across the occlusal surface, or where the gold surrounds a mass, as a crown base or a ring. The writer has a taper column of brass on which very many rings of wax have been made and cast in gold by different operators and methods, and the only rings the writer has ever seen that were actually as large as the mandrel on which they were formed were those cast over artificial stone; and by using a grade of stone that expands on setting they would pass over the base of the mandrel or taper column easily.

We have, then, as the best results available by the present materials and present technique a final contraction error for inside dimensions of, at best, 0.8 per cent., and from this up to 3 or even 6 per cent., according to the materials and technique used—which will prevent a gold restoration from going to place over an outside dimension. In such a condition, if the gold can be held it can be stretched, thus correcting this most serious error. The surface errors and the distortion errors may be enormous; they may be mistaken for expansion, and are generally sufficient to prevent an otherwise perfect reproduction, if we had it, from going to place; hence the making of a joint within 1/1000 in. close at every point around cavities by casting a perfect inlay is at present impossible. The uncontrollable contraction of the gold

also makes this a physical impossibility as yet.

FINAL CONTROL IN THE BEVELING OF THE CAVITY MARGINS AND BURNISHING OF THE INLAY.

Hence we must use a mechanical means for closing within 1/10,000 inch every part of the margin of an inlay, and this the writer believes can be accomplished with even all our at present uncontrolled errors, involved in even the best technique, by preparing all cavities with bevel margins and providing a chisel-shaped margin of gold to cover every border of every cavity, which margins must be of a pliable metal to be burnished and finished to the tooth while the cement is soft. This means only pure gold for margins, and added strength should be gotten wherever required by casing in it iridio-platinum, preferably in the form of threaded bars.

ESTABLISHMENT OF RESEARCH LABORATORIES ADVOCATED.

The art of casting will be greatly benefited by the perfecting of pattern and impression waxes free from elasticity error but with good expansion and wide working range, and by an investing medium that will expand on heating 2 or 3 per cent. linear, and also be hard and strong to permit of high pressures.

The profession should establish research laboratories equipped and maintained for continually following up and perfecting these fundamental requirements for our professional services, as the rapid march of dental progress is constantly presenting new problems and methods that are based upon materials and principles that have not been studied in connection with the other and older sciences.

It is not the writer's privilege to say what the amount of error is in the technique of his fellow practitioners, but he knows both from the technique used and the results shown that it is often very large indeed, and that very few in the profession are regularly producing gold inlays that do not show at some point a trace of a cement line, which high ideal in the majority of cavities it is today possible to attain. This fact, viz, our imperfect results, and the ignorance regarding the principles and physical properties of the materials involved, which ignorance causes these imperfect results, have induced the writer to make this exhaustive study. He believes that the demand of the profession of tomorrow will be that every dentist assuming to render the best service must make himself familiar with the physical properties and the laws governing the behavior of the materials which determine the perfection of his service. In other words, he must know the fixed conditions, and familiarize himself and the variable conditions to those fixed conditions, to produce the highest possible perfection. For example, if any dentist will take the impression wax that he uses and study Figs. 1, 2, and 3, and Table II, he will learn faithfully the behavior of that impression wax, and note how he shall manipulate it to produce the least amount of error, and then turn to the investments shown graphically in Fig. 5, and note at what temperature the investment which he uses should be cast in order to produce the maximum expansion, he will probably, in a few minutes, see at which step he can reduce his present casting errors several fold.