EFFECTIVE THERMAL EXPANSION OF CASTING INVESTMENT

by

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INTRODUCTION

The desirable physical properties of cast gold alloys have appealed to dental practitioners ever since Taggart introduced the lost wax process to the profession in 1907 (1). The comparative clinical permanence of gold castings has been reported by Moore and Stewart (2) whose data show a lower incidence of recurrent decay at the margins of gold castings than at the margins of silver amalgam restorations. The mechanical ability of cast gold to restore occlusion (3) and protect weakened tooth structure (4) is well accepted by the profession today.

It is presumed that the clinical success of a cast restoration is dependent on accurate fit in or on the prepared tooth. Early dental castings were regularly too small. The shrinkage of the metal during the casting procedure was considered to be the primary cause (5). This casting shrinkage has been found to be unavoidable. Other factors affecting the dimension of the final casting include: wax pattern shrinkage or expansion (6); setting expansion of the investment material, either normal (7) or hygroscopic (8); and thermal expansion of the investment.

An accurate fit depends on balancing the contractions and expansions of the materials used in the procedure. This concept is called the Theory of Compensation, which may be stated algebraically as follows:

GOLD SHRINKAGE on cooling	+PATTERN SHRINKAGE forming temp. to room temp.	=PATTERN EXPANSION room temp. to investing temp.	+INVESTMENT SETTING EXPANSION	+INVESTMENT THERMAL EXPANSION

This equation has been thoroughly analyzed by Coleman (9) and the initial work done at the National Bureau of Standards was in support of the Theory of Compensation. However, the measurements taken of the dimensional changes of the various materials involved in the casting procedure were idealized in the early work when compared to the actual environment of an invested pattern in a casting ring. Coleman measured the casting shrinkage of a long rod of gold, 30 centimeters long by 1 centimeter in diameter (10); Price measured dimension change in wax by using a wax rod of similar dimensions (11); setting expansion of investment was measured on a sample 30 centimeters long setting in a V-shaped trough; thermal expansion of the investment was measured on a cylinder 20 centimeters long by 1.5 centimeters in diameter in a quartz tube dilatometer.

Since that time there have been attempts to measure dimensional changes under conditions more closely related to actual casting practice. Hollenback determined casting shrinkage on different shapes (12); Mahler measured the investment setting expansion in the actual ring (13); Fusayama measured mold behavior using stylized patterns (14); and Mumford measured thermal expansion in a casting ring by an indirect method (15).

In view of the need for accurately determining the precise changes in the actual casting ring it was considered desirable to continue the approach of direct measurement. The thermal expansion of investment was selected for detailed analysis since the knowledge in this area is still not well defined.

Thermal expansion exhibited in a casting ring may not be uniform (16) and may differ in amount from values derived from traditional measurement technics. The present A.D.A. Specification No. 2 for dental casting investment describes the traditional measurement method for thermal expansion. By this method the linear expansion of a long cylindrical sample is measured in a vertical oven by the reading on a dial gauge. The dial is actuated by a quartz rod resting on the upright sample. The test is performed on a sample "1.2 cm. in diameter by approximately 20 cm. in length by the fused quartz expansion apparatus method, or by the use of equipment of equal accuracy" (17). The linear expansion expressed in percent supposedly describes the thermal expansion under practical conditions. However, a mold cavity for a clinical casting is a complex shape and for individual restorations is seldom more than 1 cm. in its greatest dimension. An MOD inlay might be likened to the shape of a staple, a full crown to a thimble, and a Class II to a section of an "L" beam. In no case does the mold for a clinical casting resemble a simple rod. There is a reason to suspect that linear expansion of a rod may not predict the actual expansion within a complex mold cavity.

Effective thermal expansion is defined in this study to be the actual expansion that occurs in the dimensions of a mold cavity in a casting ring that directly affects the fit of the casting. Effective setting expansion measurements have been made (18) which demonstrate variations from values obtained by the conventional linear expansion in a trough method. It would be important to know if thermal expansion behaves similarly. If differences exist between effective thermal expansion and traditionally determined thermal expansion measurements it should be possible to use this information to predict the significant dimensional changes of a given investment and thereby produce more accurate castings.

Attempts at measuring effective thermal expansion have been made by other investigators. Mumford (19) invested an MOD pattern to which he had attached a short wire at each gingival margin. The attached end of this wire, in the form of the cross arm of a "T," was embedded in both the pattern and the investment. The free end of the wire, or long leg of the "T," protruded through the casting ring. Index marks on the protruding wires permitted measurements at different temperatures which were interpreted as measures of actual mold expansion. Frictional effects of the wires passing through the investment were lessened by a grease coating; nevertheless, possible frictional effects are actually unknown with this technic. Mumford found that certain factors studied affected the thermal expansion of the investment in ways not predicted by the conventional (i.e., A.D.A. Specification) method.

Hollenbeck (20) embedded a quartz cube in a specially designed flask mounted in a custom oven. The quartz piece could be moved in the thermally expanded mold cavity by sliding push rods which protruded through the flask. He measured the size of the mold cavity as being the size of the quartz plus the total lateral movement of the quartz in the expanded investment. He assumed no crumbling of the investment into the cavity to affect the position of the quartz in contact with the ends of the mold cavity. Frictional effects of the push rods were undetermined. Although the cube scarcely represents the complex shape of a practical dental casting, the study of Hollenbeck reflects the concern for precisely determining effective thermal expansion.

Fusayama (21) studied thermal expansion using stylized mold forms and described variations in casting shrinkage as dependent on mold shape. All these investigators have shown concern for measuring the actual thermal expansion of the mold cavities and the possibility that actual thermal expansion may show differences compared to the conventional values. The methods employed to date have not resolved this question.

PURPOSE OF THIS INVESTIGATION

It was the primary purpose of this investigation to devise a method for measuring the thermal expansion of casting investment which would be a direct measure of the actual enlargement of the mold in the dimensions reflecting the fit of the actual casting. This actual mold expansion has been called effective thermal expansion.

The second purpose of this investigation was to determine the influence of certain manipulative variables on this effective thermal expansion.

The third purpose of this investigation was to compare the values for effective thermal expansion with those values obtained from the traditional method of measuring linear thermal expansion.

MATERIALS AND METHODS

Investments Investigated. Cristobalite Investment for Inlays (batch #10366R31, Kerr Manufacturing Company) contains appreciable amounts of silica in the form of cristobalite and demonstrates a relatively large thermal expansion. This investment, termed Cristobalite in this investigation, was chosen as representative of an A.D.A. approved Type I investment.

Beauty Cast Inlay Investment (batch #1125604, Whip Mix Corporation) was the other material investigated. Beauty Cast has a relatively low thermal expansion and is formulated to be usable with or without a water immersion technic. Beauty Cast is representative of an A.D.A. approved Type II investment.

Standard Conditions. The standard conditions of manipulation were defined as those conditions recommended by the manufacturers of the two materials. These standard conditions represent the manipulation that is probably most used in practice. Table 1 lists the standard conditions.

TABLE 1

STANDARD CONDITIONS

CRISTOBALITE

W/P ratio = .38; Spatulation time = 8 seconds; Asbestos liner - centered in ring

BEAUTY CAST

W/P ratio = .38; Spatulation time = 20 seconds; Asbestos liner - centered in ring

Water immersed - yes   Immersion and setting temp. 100° F

Manipulative Variables. These two investments were investigated both with recommended manipulation, described above as standard conditions, and with certain variables of manipulation that might be used in practice. Variations in water-powder ratio, spatulation time, and ring liner placement were studied for both materials. With Beauty Cast, which is formulated to permit hygroscopic setting expansion, the effects of temperature and water immersion conditions while setting on the effective thermal expansion were also investigated.

Rationale for Variables. Water-powder ratio and spatulation affect setting expansion of gypsum (22). Setting expansion of gypsum has been described as resulting from the thrust of forming crystals of the dihydrate $CaSO_4$ $2H_20$ (23). Changes in the amount of setting expansion might be expected to change the separation distance of adjacent particles of the refractory component of a gypsum investment. If the thermal expansion is partly determined by the separation distance of these refractory particles, usually quartz, it might be expected that an increased setting expansion would result in a decreased thermal expansion of a given investment.

If proportioning is performed without measuring the powder weight and water volume it is possible to obtain a workable mix that has a lower water-powder ratio than standard conditions. A lower W/P ratio would be expected to increase setting expansion (24). The W/P ratios investigated, in addition to standard conditions were: Cristobalite W/P = .35; Beauty Cast W/P = .28.

Increased spatulation can be used to purposely increase the setting expansion. If spatulation time is not monitored increased spatulation time may result. Double the standard condition was the variable chosen for increased spatulation because it represents the near maximum spatulation time that can be used while retaining enough fluidity of the investment to pour into the ring.

Variations in asbestos liner placement, centered (i. e., short of the open ends of the ring by 3 mm) or full length, have been reported to affect expansion of the mold cavity as measured by the fit of the final casting (25). Thermal expansion near the open end of a ring with a centered liner might be restricted by lack of an asbestos cushion in this region. Full-length liner placement has been recommended and may be purposely used. Careless liner placement could permit the liner to slip and become flush with the end of the ring.

Full-length and centered (3 mm from ring ends) liner placement was studied in this investigation with the centered liner being taken as the standard condition.

It has been shown that effective setting expansion of a casting investment used in the hygroscopic technic is temperature-dependent (26). An early technic (27) proposed using the hygroscopic material setting in a warm water bath which suggests that total mold expansion may be related to the temperature of investing as well as any hygroscopic effect. Immersion conditions at different temperatures are of interest to separate the possible effects of temperature and immersion. The temperature chosen for investigation were: 72° F (room temperature); 100° F (standard conditions); and 110° F. These are commonly used conditions in dental laboratory practice. Using Beauty Cast, at each of these temperatures, the effect of immersion was investigated by having one condition not immersed and the other immersed at each of the temperatures described.

As will be described, the method used for measuring effective thermal expansion was an X-ray method whereas the conventional method used for measuring thermal expansion was the quartz tube-dilatometer method.

The summary of the conditions investigated with the X-ray technique is presented in Table 2. The summary of the conditions investigated with the quartz tube dilatometer method is presented in Table 3. The method of sample preparation for the dilatometer method made it impractical to use an asbestos liner or to vary the temperature and immersion conditions.

TABLE 2 - EXPERIMENTAL DESIGN - X-RAY TECHNIQUE

CRISTOBALITE

Condition	W/P Ratio	Spatulation	Liner
1. STANDARD	.38	8 seconds	centered
2. Decreased W/P	.34	8 seconds	centered
3. Increased Spatulation	.38	16 seconds	centered
4. Liner	.38	8 seconds	flush

For each condition ten samples were used, n=10

BEAUTY CAST

Condition	W/P	Spatulation time in seconds	Liner	Immersion	Temperature while setting in degrees F
A. STANDARD	.30	.20	centered	yes	100
B. Decreased W/P	.28	.20	centered	yes	100
C. Increased Spatulation	.30	.40	centered	yes	100
D. Liner	.30	.20	flush	yes	100
E. Temperature	.30	.20	centered	yes	72 (room temp)
F. Temperature	.30	.20	centered	yes	110
G. Immersion	.30	.20	centered	no	100
H. Immersion + Temperature	.30	.20	centered	no	72
I. Immersion + Temperature	.30	.20	centered	no	110

Note: Conditions A., E., and F. are used to compare the effects of temperature differences while immersed; condition G., H., and I. the effects of temperature differences while not immersed; and conditions A., E., F. vs. G., H., I. the effects of immersion vs. non immersion.

For each listed condition ten samples were used, n=10.

For the entire investigation a random order of procedure was used.

TABLE 3

EXPERIMENTAL DESIGN - QUARTZ TUBE DILATOMETER METHOD

CRISTOBALITE

Condition	W/P Ratio	Spatulation Time
1. STANDARD	.38	8 seconds
2. Decreased W/P	.34	8 seconds
3. Increased Spatulation	.38	16 seconds
	BEAUTY CAST	
A. STANDARD	.30	20 seconds
B. Decreased W/P	.28	20 seconds
C. Increased Spatulation	.30	40 seconds

Investment expansion at 700° C for Cristobalite and at 500° C for Beauty Cast was determined by both the X-ray and the Quartz Tube Dilatometer methods.

X-Ray Method - General. X-ray images of a full crown mold at room temperature prior to burning out the mold and at the burn out temperature can be compared to give measurements of mold thermal expansion. A precisely definable index is necessary for reproducible measurements. Small metal spheres, 0.7 mm in diameter, attached to the wax pattern and two-thirds embedded in investment were used as indices in this study. A measuring microscope was used to measure the distance between ball image centers. The distances measured between the images of the ball centers before and after burn out temperature were used to determine the percent of effective thermal expansion.

One pair of spheres was used to determine the mold expansion at the gingival plane and another pair of spheres was used in the same mold to determine expansion at the pulpal wall plane of a full crown mold cavity. Since this technique does not require the movement of wires or rods through the investment, frictional effects are not involved. Van Aken (28) used a similar technique to measure setting expansion of investment. It was thought desirable to modify his technique to the measurement of thermal expansion in this study.

A jig was made to support a custom oven and a cassette platform in a fixed relation to the X-ray source. By directing the beam axially through the casting ring it was not necessary to cut ports in the ring as Van Aken had done (29). The ring was clamped by invar rods to keep it stationary within the oven. Ports in the custom oven permitted the X-ray beam to traverse the investment with the least impediment. The X-ray method scheme is shown diagrammatically in Figure 1.

Pilot studies using the apparatus described demonstrated the feasibility of the technique. The standard error of the mean of repeated measurements of a given image was less than 5 microns. It should be noted that 5 microns in a 10 mm dimension results in a figure of .05% as the standard error of the mean over the distance measured.

X-Ray Method - Technique. Each sample for X-ray image measurement was an invested full crown wax pattern with attached carbide ball bearing index markers. The pattern was molded on a steel die by the pour and press method (30). Wax distortion was not a consideration in this investigation because the fiducial measurements were made after the investment had set. The pattern was sprued on its largest cusp and was axially centered in the ring with the gingival margin of the pattern 9 mm from the open end of the ring. A new chromel-alumel thermocouple was fed through a small hole in the side of the ring, curving around the pattern to a point centrally located within the investment core inside the crown pattern. The spatulation and pouring of the investment were done under vacuum[1].

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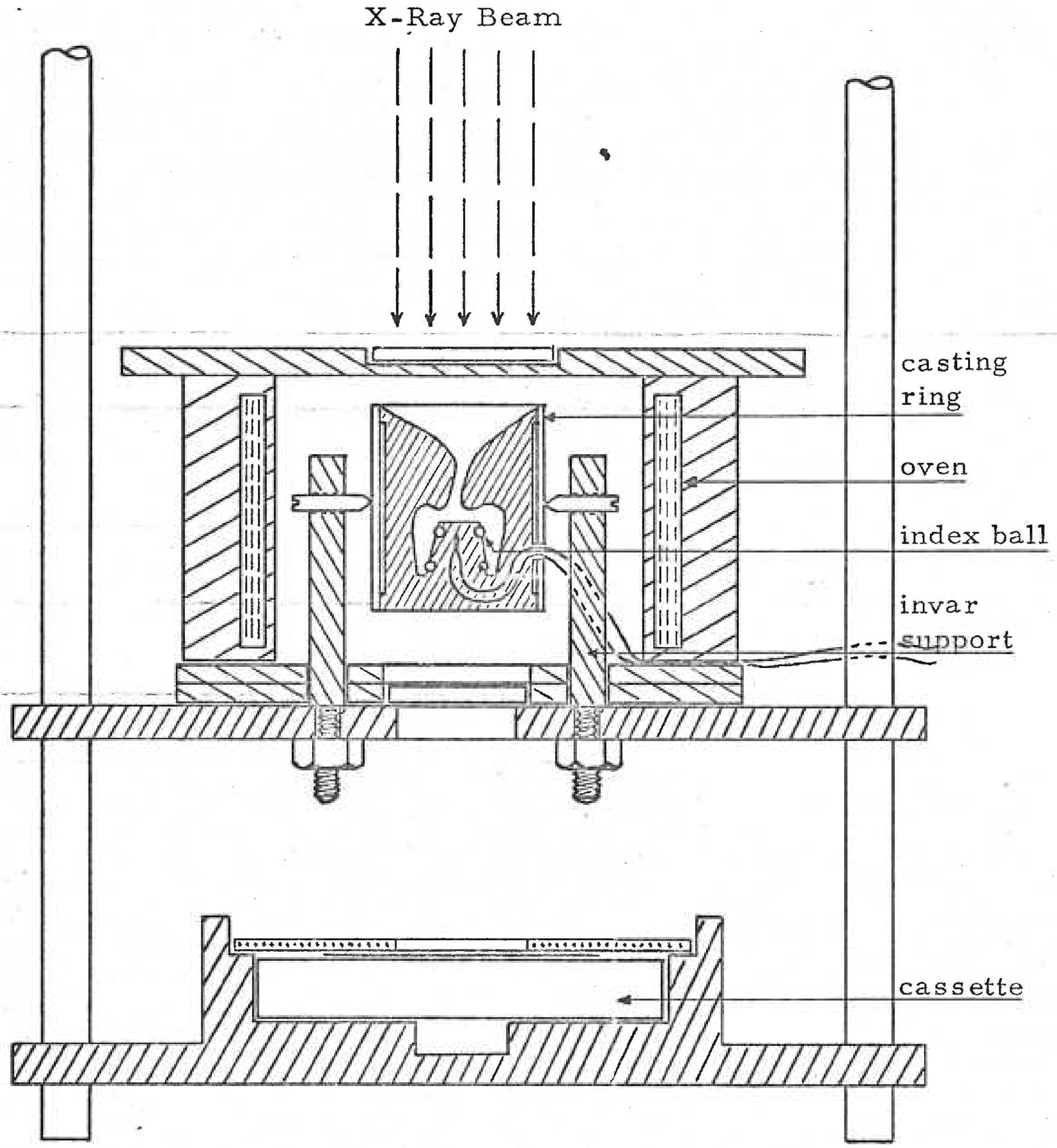
[1] Vac-u-spat and Vacu-vester, Whip Mix Corp., Louisville, Kentucky.

FIGURE 1 X-Ray Apparatus Scheme



The invested sample was stored overnight in a covered plastic dish to prevent excessive dehydration.

The ring with the set investment was mounted in the invar clamps attached to the base of the oven. The oven proper, in the general form of a hat, was set over the sample. The thermocouple wires exited through prepared grooves in the oven base. A first X-ray exposure was made at room temperature prior to burn out on one portion of a sensitized glass plate[1]. The glass plate was enclosed in a light-proof custom cassette. Over the cassette was placed a sheet of lead which had a hole to permit the passage of X-rays through the area of interest.

The oven was started and the sample heated at the rate called for in the A.D.A. Specification procedure (31). Heating rate was monitored with an X-Y recorder[2] attached to the thermocouple. Final temperature was determined with a bridge potentiometer[3].

When the burn out temperature had been reached in the investment core a second X-ray exposure was made on the remaining portion of the same sensitized plate after first sliding the cassette along its supporting slot to the proper position. The plane of the

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[1] Eastman Autoradiographic Plate, Type No Screen, Eastman Kodak Co., Rochester, New York.

[2] Moseley Autograf Model 3S with custom time base input.

[3] Leeds and Northrup Model #1220417, Leeds and Northrup, Philadelphia, Pennsylvania.

emulsion was held constant by the apparatus regardless of which portion of the plate was being exposed. Before and after burn out, exposures were made on the same plate, held in a fixed plane, to minimize possible differences between plates or development procedures. Plate processing was done according to manufacturer's instructions (32).

The processed plate was placed under a measuring microscope[1] with the horizontal cross-hair biesecting both ball center images of interest. The distance between ball center images was measured. Pilot studies had shown that measurements between ball centers were reproducible with greater accuracy than measurements between tangents at the ball edges. The edge of a projected X-ray image is inherently fuzzy under magnification, and this phenomenon decreases the reproducibility of repeated measurements made to an edge of an image.

Quartz Tube Dilatometer Method. This method, the one prescribed by the A.D.A. Specification No. 2, was performed with the use of a vertical oven[2] to heat the sample. The apparatus including a quartz tube into which the sample is placed, with a quartz rod resting on the sample. The rod extended out of the top of the

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1. Gaetner Scientific Corp., Chicago, Illinois. Type M-301 micrometer slide calibrated to read by vernier scale to 1 micron.

2. Gaetner Scientific Corp., Chicago, Illinois, serial #76AK.

oven and actuated a dial gauge[1]. It has been shown (33) that thermal expansion measurements made in this sort of apparatus are dependent upon the restricting stress provided by the weight of the quartz rod plus the spring tension of the dial gauge. These effects were not separately studied in this investigation, but are mentioned here to suggest again the possibility that effective thermal expansion may not be reflected in the linear expansion method. It should be noted that the A.D.A. Specification No. 2 does not define the restrictive stress to be used.

The apparatus used in this investigation made use of a sample 3 inches in length (7.62 cm.) instead of the 20 cm. specified, but is acceptable for the test under the qualification "or by the equipment of equal accuracy" (34). The 3 inch rods of investment were made by pouring the mixed investment into a split brass mold at room temperature and atmospheric pressure. A chromel-alumel thermocouple was embedded in the center of the rod to permit temperature monitoring of the investment during the test.

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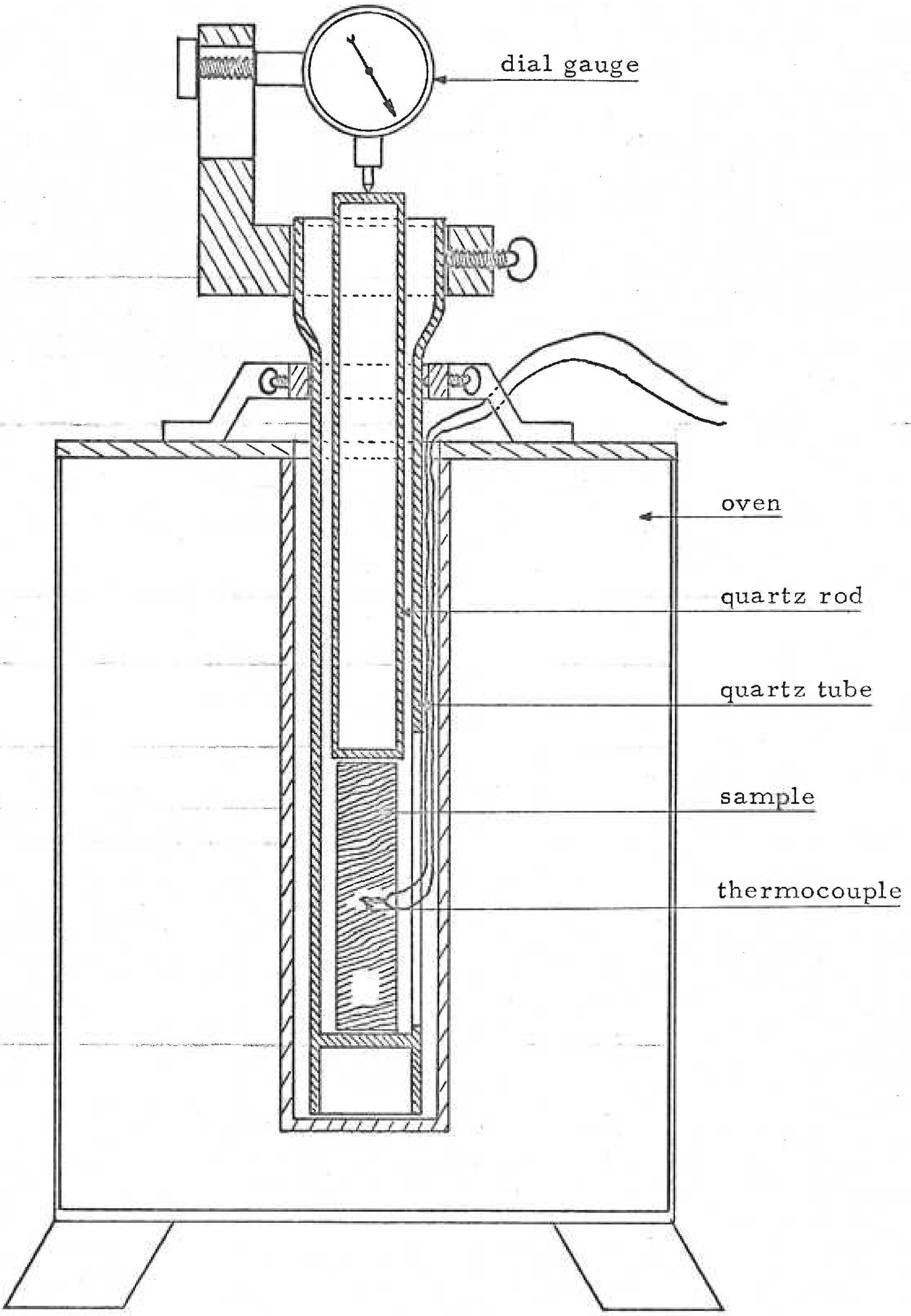
1. Standard No. 241, Standard Gauge Co., Poughkeepsie, New York. This dial gauge has markings to read in units of 0.0001 inches.

FIGURE 2 Quartz Tube Dilatometer Scheme



RESULTS AND DISCUSSION

X-Ray Method - Cristobalite. The data and its statistical analysis are presented in Appendix A. The level of significance chosen for the analysis was .05. The term "very significant" was chosen to denote significance at the level of .01.

The expansion mean values and their respective standard deviations are presented in Table 4. Expansion values are expressed both in percentages, which is the conventional form, and in microns of real expansion. Real expansion figures were obtained by multiplying the percent expansion divided by 100, times the actual die dimension. Real expansion is an expression of effective thermal expansion, expressed in microns, unaffected by X-ray projection enlargement.

The data was subjected to an analysis of variance procedure, two-way with replications. The test is stated to require the assumption of homogeneity of variances (35). As measured by Cochran's Test (36) the condition of homogeneity of variances is not met because of especially high variances with the "Flush Liner" condition. Some authors (37) believe that the analysis of variance test is sufficiently robust to be useful in the face of variations from its assumptions. Scheffé states (38) "inequality of variances in the cells of a layout has little effect on inferences about means if the cell numbers are equal".

TABLE 4

CRISTOBALITE EXPANSION FROM ROOM TEMPERATURE TO 700°C
Mean and Standard Deviation in Percent and Real Microns

POSITION	CONDITION			
	STANDARD	W/P .34	16 Seconds Spatulation	Flush Liner
Pulpal in %	1.50 (.11)	1.51 (.24)	1.57 (.18)	1.75 (.31)
Gingival in %	1.00 (.13)	1.03 (.16)	.90 (.10)	1.08 (.37)
Pulpal in microns	115 (9)	115 (18)	120 (.14)	133 (23)
Gingival in microns	94 (12)	96 (15)	84 (9)	108 (35)

TABLE 5

CRISTOBALITE - PULPAL - GINGIVAL DIFFERENCES

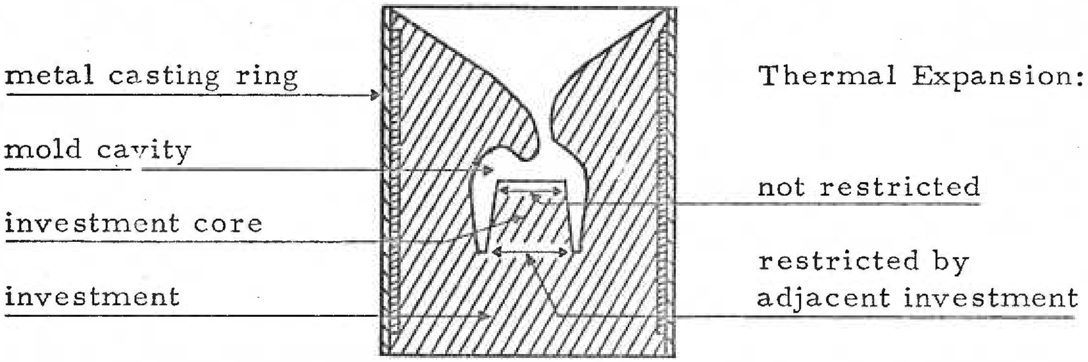
CONDITION	Pulpal - Gingival in %	Pulpal-Gingival in microns
STANDARD	.50	21
W/P .34	.48	19
16 Seconds	.67	35
Flush Liner	.66	31
$\bar{X}$	.58	27

The two-way analysis of variance with replications was carried out for all four conditions, pulpal and gingival positions, with ten replications per cell (Appendix A, Tables 16 and 17). The analysis of variance showed a very high significance of non-equality between pulpal and gingival positions. Interaction was not significant, thereby prohibiting individual comparisons of cell means. The average differences between pulpal and gingival expansions are presented in Table 5.

Expansion at the pulpal plane was shown to be greater than the expansion at the gingival plane. The difference in means between the pulpal plane and the gingival plane with Cristobalite was in the order of 0.6% or 27 microns. The expansion difference could be explained on the assumption that the expansion of the investment core on heating is more restricted by adjacent investment near the gingival plane than at the pulpal plane. This concept is shown diagrammatically in Figure 3.

FIGURE 3

PROPOSED EXPLANATION FOR EXPANSION VARIATION



The analysis of variance resulted in an F value that was not significant between conditions. Under the conditions of this investigation it was not possible to demonstrate thermal expansion differences between investing conditions with Cristobalite.

The high variance of the "Flush Liner" condition as measured by Cochran's Test suggests that this condition has a variability significantly higher than the other conditions and perhaps should not be recommended for use with Cristobalite.

Quartz Tube Dilatometer Method - Cristobalite. Table 6 presents the results of five replications with each of the three conditions investigated. By the one-way analysis of variance no differences between conditions was demonstrated.

TABLE 6

SPECIFICATION TESTING - CRISTOBALITE $\bar{X}$, S

Percentage Expansion

	$\bar{X}$	S	n
Standard	1.26	.02	5
W/P .34	1.27	.05	5
16 Seconds	1.25	.01	5

Cristobalite - Combined Results. Table 7 presents the results that were obtained for comparisons between the two methods of testing used in this investigation.

TABLE 7

CRISTOBALITE EXPANSION - PULPAL, SPECIFICATION, GINGIVAL

Percentage Expansion
Standard, W/P .34, and 16 Seconds Pooled

	Pulpal in Ring n=30	Specification Test n=15	Gingival in Ring n=30
$\bar{X}$	1.53	1.26	.98

It was found that the mean values with the quartz tube dilatometer or A.D.A. Specification Test lie about halfway between the effective thermal expansion of the pulpal plane and the gingival plane of a clinical size mold cavity. The A.D.A. Specification Test appears to predict the average expansion of the mold cavity, but does not accurately predict the effective expansion in the two planes investigated. Appendix A, Table 19 presents the statistical analysis.

It should be noted that the standard deviations of the A.D.A. Specification Test here reported are approximately a full order of magnitude lower than the standard deviations of the X-ray technique. Scheffé's method for multiple comparisons is known to be useful in analyzing such data and is also accurate when used with sample sizes that are not equal (39).

The X-ray technique used in this investigation is quite complicated and time-consuming; however, it appears to be a more accurate measure of effective mold expansion with Cristobalite in the specific planes studied in this investigation.

X-Ray Method - Beauty Cast. The data and its statistical analysis are presented in Appendix B. The expansion mean values and their respective standard deviations are presented in Table 8. The assumption of homogeneity of variances was not met as measured by Cochran's Test for Beauty Cast thermal expansion expressed in percentage, but was satisfied when microns of real expansion values were used (Appendix B, Tables 30 and 32). The two-way analysis of variance with replications was performed for all nine conditions, pulpal and gingival positions, with ten replications per cell using the percentage values and separately using the micron values.

Differences between the pulpal and gingival positions are indicated by a highly significant F value for the analysis using the percentage values, but there is no significant difference between pulpal and gingival using the values expressed in microns. For Beauty Cast as for Cristobalite there was generally a greater thermal percentage expansion in the pulpal plane than in the gingival plane. Unlike Cristobalite the real expansion in the two planes was not found to be different (Appendix B, Tables 30 and 32).

TABLE 8

BEAUTY CAST EXPANSION FROM ROOM TEMPERATURE TO 500°C
Mean and Standard Deviation

Expansion in % POSITION		CONDITION								
		Room Not	Room Im	100 Not	100 Im STANDARD	110 Not	110 Im	W/P .28	40 sec.	Flush Liner
Pulpal	$\bar{X}$	.69	.71	.37	.40	.42	.39	.53	.66	.31
	s	.17	.19	.11	.17	.22	.25	.27	.34	.22
Gingival	$\bar{X}$	.54	.46	.42	.41	.35	.37	.48	.57	.22
	s	.11	.09	.12	.11	.15	.20	.07	.20	.13
Expansion in microns										
Pulpal	$\bar{X}$	53	53	28	30	32	29	41	50	23
	s	13	14	9	13	17	19	21	26	16
Gingival	$\bar{X}$	51	43	39	38	32	35	45	53	20
	s	10	9	11	11	14	19	7	18	12

Beauty Cast, unlike Cristobalite, showed a high significance of non-equality between conditions of investment manipulation. Scheffé's Test for multiple comparison (40) is reported in Appendix B, Tables 31 and 33. It was found that there was no difference between the average of "Not Immersed" conditions and the average of "Immersed" conditions. On the other hand it was found that the average expansion of the "Room Temperature" conditions was larger than the average expansion of the "100° F" conditions. The effective thermal expansion of Beauty Cast was shown to be more when the investing temperature was room temperature as compared to 100° F. However, no difference was demonstrated between the 100° F and 110° F investing conditions. Water immersion during investing did not appear to influence effective thermal expansion.

Quartz Tube Dilatometer Method - Beauty Cast. Table 9 presents the results of five or more replications with each of the three conditions investigated. Also shown are the corresponding conditions of effective thermal expansion of Beauty Cast with the X-ray technique.

TABLE 9

SPECIFICATION TESTING - BEAUTY CAST $\bar{X}$, S

Percentage Expansion

	$\bar{X}$	S	n
Standard	.45	.05	9
W/P .28	.44	.01	5
40 Seconds	.43	.03	5

The named "Standard Conditions" are not directly comparable since the standard conditions of manipulations for the X-ray technique used immersion in a 100° F water bath while the standard conditions for the A.D.A. Specification Test made use of a sample setting at room temperature and not immersed. With Beauty Cast, thermal expansion measured by the quartz tube dilatometer method revealed no differences between conditions of investment manipulation (Appendix B, Table 34).

Beauty Cast - Combined Results. Table 10 presents the results that can be compared between the two methods of testing used in this investigation.

TABLE 10

BEAUTY CAST EXPANSION - PULPAL, GINGIVAL, SPECIFICATION

Percentage Expansion

Room Temperature Not Immersed, W/P .28, and 40 Seconds Pooled

	Pulpal in Ring n=30	Gingival in Ring n=30	Specification Test n=19
$\bar{X}$	.63	.53	.44

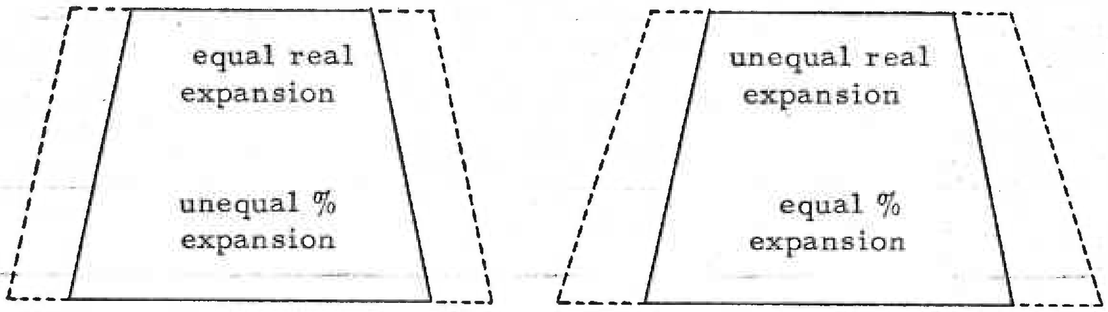
The mean values with the A.D.A. Specification Test method do not lie between the effective thermal expansion of the pulpal and gingival expansion as they did for Cristobalite. By the Scheffé Test the A.D.A. Specification method gives values which are not different for the effective thermal expansion at the gingival plane but which are lower (as was the case with Cristobalite) than the values for effective thermal expansion at the pulpal plane.

Real Expansion. It was shown that with Beauty Cast the real expansion expressed in microns did not show a difference between the pulpal and gingival planes but that such a difference did exist when percentage values were used. The percentage values represent the mode required by the A.D.A. Specification No. 2.

A full crown pattern requires a taper of the tooth preparation to permit the placement and cementation of the casting. The pulpal and gingival diameters before burn out are different, the pulpal being smaller than the gingival. Assuming no axial expansion of the mold the pulpal must expand more in percentage than the gingival to achieve equal real expansion of the entire mold. See Figure 4.

FIGURE 4

DIAGRAM OF MOLD CORE EXPANSION



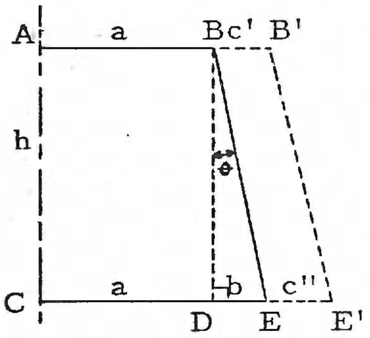
For a given difference between pulpal minus gingival thermal expansion expressed in percentage the fit of the casting requires equal real expansion in the two planes. Equal real expansion will be determined by:

1. angle of taper of the preparation
2. vertical distance between the pulpal and gingival
3. pulpal diameter and gingival diameter.

These relationships are presented in Figure 5.

FIGURE 5

GEOMETRIC CONSIDERATIONS



Let AC = H = axis of preparation
AB = CD = a = 1/2 pulpal diameter
CE = a + b = 1/2 gingival diameter
BB' = 1/2 pulpal expansion = c'
EE' = 1/2 gingival expansion = c''
and % expansion expressed
$\frac{c'}{a} = P_{ex}$ $\frac{c''}{a + b} = G_{ex}$

$\tan\theta = b/h$ $b = h \tan\theta$

$c' = aP_{ex}$ $c'' = (a+b)\ G_{ex}$

for equal real expansion $c' = c''$

$a\ P_{ex} = (a+b)\ G_{ex}$

$$P_{ex} = G_{ex} + \frac{h \tan\theta G_{ex}}{a}$$

For equal real expansion
pulpal % expansion must
exceed gingival % expansion
by the quantity

$$\frac{h \tan\theta G_{ex}}{a}$$

For a given pulpal and gingival expansion in percentage:

1. A long preparation (large h) requires less taper and/or a large diameter tooth. The clinician has a challenging problem to minimize the taper of a long tooth preparation, but he must attempt to do so lest the resulting casting not fully seat. As a corollary, the short crown tooth requires more taper. Excessive taper of a short

preparation well lessen ultimate retention (41). It would probably be advisable in some cases to lessen the taper and lengthen the preparation, even if a prior gingivectomy were required, to achieve adequate retention and proper fit in such a situation.

2. A large diameter tooth requires more taper and/or a long tooth. The large diameter tooth will permit more taper, but too much taper will cause the unwanted effect of inadequate pulpal expansion which will prevent the seating of the casting.

Setting Expansion Considerations. With Beauty Cast, effective setting expansion measurements have been reported (42) that show generally greater setting expansion in the gingival plane than in the pulpal plane and also that this difference is lessened with increasing environmental temperature of investing. For accurate casting shrinkage compensation the total of setting and thermal expansion should be uniform throughout the mold (except as may be modified by uneven casting shrinkage phenomena). The generally greater effective thermal expansion at the pulpal, expressed in percentage, balances the reverse effect for setting expansion in a well fitting casting. The differences are small with both types of expansion using Beauty Cast except that the setting expansion difference appears larger at room temperature investing conditions. It is therefore recommended that a warm water bath investing technic be used to equalize setting and thermal expansion distortions with Beauty Cast.

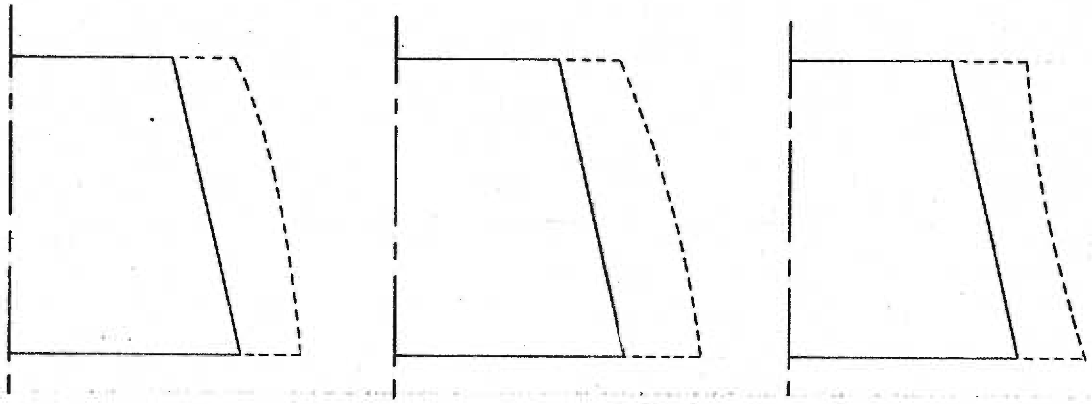
With Cristobalite the setting expansion is very small. The percentage difference between pulpal and gingival effective thermal expansion is required to permit equal real expansion in the two planes.

Future Investigation. Neither effective thermal expansion at planes other than the pulpal and gingival nor effective thermal expansion axially have been determined. The X-ray technique herein described could be used for such a study.

It would be important to know what effective thermal expansion occurs in other planes between the pulpal and gingival. If expansion is irregular between these two planes the plane of least real expansion would determine the possibility of seating the casting. Figure 6 shows some of the possibilities of irregularity.

FIGURE 6

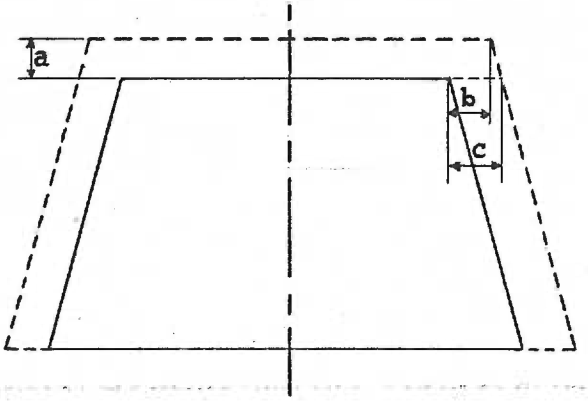
SOME POSSIBILITIES OF IRREGULAR EXPANSION



Axial expansion would modify the fit consideration of pulpal and gingival expansion when expressed in percentage. With more axial expansion the less would be the required difference between pulpal and gingival expansion to achieve proper fit. This idea is shown diagrammatically in Figure 7.

FIGURE 7

EFFECT OF AXIAL EXPANSION



a. possible axial expansion

b. pulpal expansion with axial expansion

c. pulpal expansion if no axial expansion

SUMMARY AND CONCLUSIONS

An X-ray method was devised to measure the effective thermal expansion of dental casting investment in a dental mold. Two pairs of index markers (metal balls) were partially embedded in the wax pattern before investing. One pair was placed on the axial at the pulpal plane diameter and the other on the axial at the gingival plane. The set investment retained the metal balls. The effective thermal expansion was determined as the difference in linear dimension between the centers of X-ray images of a pair of metal balls before burn out and at burn out temperature. The method was sufficiently sensitive to reveal differences in expansion across the two planes of a full crown mold when heated to burn out temperature. The percentage expansion at the pulpal plane was generally greater than at the gingival plane for both Cristobalite and Beauty Cast.

When Cristobalite was manipulated under four different sets of conditions, no differences in mean effective thermal expansion was demonstrated. The use of an asbestos liner that was flush with the end of the casting ring resulted in effective thermal expansion measurements that were excessively variable when compared to the other conditions investigated. Such variability would suggest a lack of reliability with the procedure of using the "flush liner" for practical castings.

When Beauty Cast was manipulated under nine sets of different conditions, differences in effective thermal expansion were demonstrated between conditions. The effective thermal expansion of Beauty Cast was shown to be more when the investing temperature was room temperature as compared to 100° F. However, no difference was demonstrated between the 100° F and 110° F investing conditions. Water immersion during investing did not appear to influence effective thermal expansion.

The thermal expansion test in the A.D.A. Specification No. 2 for casting investment for dental gold alloy is simple, has low variability, and predicts approximately average effective thermal expansion. On the other hand, it does not reflect effective thermal expansion in specific planes in a dental mold for either Cristobalite or Beauty Cast.

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APPENDIX A

CRISTOBALITE DATA AND STATISTICS

TABLE 11

CRISTOBALITE - THERMAL EXPANSION - X-RAY TECHNIC

		STANDARD	W/P .34	16 Sec.	Flush Liner
Expansion in %					
Pulpal	$\overline{X}$	1.504	1.509	1.571	1.746
	S^2	.01276	.05792	.03361	.09369
Gingival	$\overline{X}$	1.001	1.026	.903	1.085
	S^2	.01763	.02489	.01064	.1346
Grand	$\overline{X}$	1.2525	1.2675	1.237	1.4155
	S^2_p	.01519	.0414	.02212	.11414
Expansion in u Calculated					
Pulpal	$\overline{X}$	114.6	114.9	119.7	133.1
	S^2	72.15	338.32	198.67	542.32
Gingival	$\overline{X}$	93.8	96	84.5	101.7
	S^2	155.73	218	91.166	1200.011
Grand	$\overline{X}$	104.2	105.45	102.1	117.4
	S^2_p	114.4	278.161	144.922	871.166

TABLE 12

CRISTOBALITE EXPANSION - STANDARD CONDITION

Test #	Measured Expansion		Percentage Expansion		Calculated Real Expansion	
	Gingival in u	Pulpal in u	Gingival in %	Pulpal in %	Gingival in u	Pulpal in u
2	101	138	.96	1.50	90	114
7	134	152	1.28	1.58	120	120
13	119	137	1.14	1.51	107	115
33	86	128	.83	1.43	78	109
35	98	153	.94	1.66	88	126
39	114	137	1.09	1.50	102	115
60	99	126	.93	1.35	87	103
61	96	135	.90	1.45	84	111
87	105	127	1.00	1.37	94	104
93	100	157	.94	1.69	88	129
$\overline{X}$	105	139	1.001	1.504	93.8	114.6
S^2			.01763	.01276	155.73	72.15
S			.13	.11	12.5	8.6

TABLE 13

CRISTOBALITE EXPANSION - W/P .34

Test #	Measured Expansion Gingival in u	Measured Expansion Pulpal in u	Percentage Expansion Gingival in %	Percentage Expansion Pulpal in %	Calculated Real Expansion Gingival in u	Calculated Real Expansion Pulpal in u
4	127	109	1.25	1.21	117	92
5	121	153	1.18	1.71	111	130
12	79	122	.76	1.33	71	101
20	124	158	1.19	1.73	111	132
36	102	140	.95	1.56	89	119
38	104	140	1.00	1.51	93	115
44	112	165	1.04	1.85	97	141
45	92	146	.84	1.63	79	124
57	116	99	1.10	1.09	103	83
62	103	132	.95	1.47	89	112
$\overline{X}$	108	136.4	1.026	1.509	96	114.9
S^2			.02489	.05792	218	338.32
S			.16	.24	14.8	18.4

TABLE 14

CRISTOBALITE EXPANSION - 16 SECONDS SPATULATION

Test #	Measured Expansion Gingival in u	Measured Expansion Pulpal in u	Percentage Expansion Gingival in %	Percentage Expansion Pulpal in %	Calculated Real Expansion Gingival in u	Calculated Real Expansion Pulpal in u
23	86	136	.83	1.47	77	112
28	104	153	1.02	1.68	96	128
43	100	122	.94	1.34	88	102
52	91	146	.85	1.60	80	122
56	77	141	.72	1.59	68	121
79	106	171	1.02	1.87	95	143
83	99	141	.94	1.56	88	119
90	108	164	1.03	1.77	96	135
98	87	113	.84	1.26	78	96
88	92	140	.84	1.57	79	119
$\bar{X}$	95	147.7	.903	1.571	84.5	119.7
S^2			.01064	.03361	91.17	198.67
S			.10	.18	9.5	14.1

TABLE 15

CRISTOBALITE EXPANSION - FLUSH LINER

Test #	Measured Expansion Gingival in u	Measured Expansion Pulpal in u	Percentage Expansion Gingival in %	Percentage Expansion Pulpal in %	Calculated Real Expansion Gingival in u	Calculated Real Expansion Pulpal in u
10	111	174	1.08	1.92	102	146
27	107	147	1.05	1.62	99	124
41	212	215	1.98	2.36	186	180
47	87	124	.83	1.40	77	107
48	128	147	1.23	1.65	115	125
53	97	158	.93	1.79	87	136
59	75	136	.69	1.51	64	115
72	83	149	.80	1.66	75	127
82	136	188	1.30	2.11	122	161
95	102	137	.96	1.44	90	110
$\overline{X}$	113.8	157.5	1.085	1.746	101.7	133.1
S^2			.1346	.09369	1200.011	542.32
S			.367	.306	34.6	23.3

TABLE 16

CRISTOBALITE ANALYSIS OF VARIANCE

Expansion at 700°C in Percent

Cochran's Test	at 99th percentile	
	k = 8 v = 9	C = .3373
Four conditions, each with pulpal and gingival		C = .3489**
	k = 6 v = 9	C = .4229
Three conditions (eliminating "Flush Liner")		C = .3679 ns

4 columns (conditions)
2 rows (positions: pulpal and gingival)
10 replications per cell

Column Mean Square	.13624	F 2.82514 ns
Degrees of Freedom	3	
Row Mean Square	6.69910	F 138.95664**
Degrees of Freedom	1	
Interaction Mean Square	.04930	F 1.02260 ns
Degrees of Freedom	3	
Within Mean Square	.04821	
Degrees of Freedom	72	

TABLE 17

CRISTOBALITE ANALYSIS OF VARIANCE

Expansion at 700° C in Microns

Cochran's Test at 99th percentile

	k = 8 v = 9	C = .3373
Four conditions, each with pulpal and gingival		C = .4261**
	k = 6 v = 9	C = .3489
Three conditions (eliminating "Flush Liner")		C = .3150 ns

4 columns (conditions)
2 rows (positions: pulpal and gingival)
10 replications per cell

Column Mean Square	947.2125	F 2.69059 ns
Degrees of Freedom	3	
Row Mean Square	14124.6125	F 40.12151**
Degrees of Freedom	1	
Interaction Mean Square	316.5458	F .089916 ns
Degrees of Freedom	3	
Within Mean Square	352.04587	
Degrees of Freedom	72	

TABLE 18

SPECIFICATION TESTING - CRISTOBALITE

Percentage Expansion

	Standard Condition	W/P .34	16 Seconds Spatulation
	1.25	1.19	1.25
	1.24	1.30	1.25
	1.25	1.26	1.25
	1.29	1.29	1.23
	1.25	1.31	1.27
$\overline{X}$	1.256	1.27	1.25
S^2	.00038	.002350	.0002
S	.019	.048	.014

Analysis of Variance

Mean Square Between	.0005267	F 0.53932 ns
Degrees of Freedom	2	
Mean Square Within	.0009766	
Degrees of Freedom	12	

TABLE 19

COMBINED RESULTS - CRISTOBALITE EXPANSION IN %, $\bar{X}$ and S

CONDITION	VARIABLE Pulpal in ring $\bar{X}$	 S	 A.D.A. Specification Test $\bar{X}$	 S	 Gingival in Ring $\bar{X}$	 S
STANDARD	1.50	.11	1.26	.02	1.00	.13
W/P .34	1.51	.24	1.27	.05	1.03	.16
16 Seconds Spatulation	1.57	.18	1.25	.01	.90	.10
Column Means	1.528		1.259		.977	
n =	30		15		30	

COMBINED RESULTS - CRISTOBALITE EXPANSION IN %

ONE WAY ANALYSIS OF VARIANCE

Mean Square Between	2.28003	F = 106.44398**
Degrees of Freedom	2	
Mean Square Within	.02142	
Degrees of Freedom	72	

SCHEFFÉ COMPARISONS $\sqrt{(r-1)F_{.95;r-1,N-r}\,MS_W \sum_{j=1}^{r} \frac{c_j^2}{n_j}}$

Scheffé Interval $= \sqrt{2(3.13)(.02142)(\frac{1}{30}+\frac{1}{15})} = .0134$

	Pulpal in Ring		A.D.A. Specification Test		Gingival in Ring
$\bar{X}$	1.528	$>$	1.259	$>$	.977

APPENDIX B

BEAUTY CAST DATA AND STATISTICS

TABLE 20 BEAUTY CAST - THERMAL EXPANSION - X-RAY TECHNIC

		Room Not	Room Im	100 Not	100 Im Standard	110 Not	110 Im	W/P .28	40 sec.	Flush Liner
Expansion in %										
Pulpal	$\overline{X}$	.693	.707	.369	.401	.423	.388	.538	.658	.309
	S^2	.02897	.03671	.0121	.02912	.0498	.06017	.07184	.11446	.04658
Gingival	$\overline{X}$	.541	.462	.419	.406	.349	.375	.481	.570	.218
	S^2	.01185	.00835	.01452	.01309	.02178	.04047	.00547	.03837	.01730
Grand	$\overline{X}$	.617	.589	.394	.4035	.386	.3815	.5095	.614	.2635
	S_p^2	.02041	.02203	.01332	.02110	.03579	.05032	.03865	.07642	.03194
Expansion in u Calculated										
Pulpal	$\overline{X}$	52.6	53.3	27.7	30.3	31.9	29	40.6	49.9	23.1
	S^2	167.822	206.677	73.122	168.233	291.877	351.55	428.711	679.877	269.65
Gingival	$\overline{X}$	50.6	43.1	39.1	38	32.4	34.9	44.6	53.1	19.7
	S^2	102.488	76.766	125.655	114.88	196.711	363.42	48.266	339.877	153.56
Grand	$\overline{X}$	51.6	48.2	33.4	34.15	32.16	31.85	42.6	51.5	21.4
	S_p^2	135.155	141.722	99.388	141.561	244.294	357.494	238.488	509.877	211.611

TABLE 21

BEAUTY CAST EXPANSION - ROOM TEMPERATURE NOT IMMERSED

Test #	Measured Expansion Gingival in u	Measured Expansion Pulpal in u	Percentage Expansion Gingival in %	Percentage Expansion Pulpal in %	Calculated Real Expansion Gingival in u	Calculated Real Expansion Pulpal in u
3	43	67	.41	.74	38	56
11	62	60	.61	.65	57	49
14	33	41	.32	.45	30	34
16	60	49	.59	.54	55	41
23	56	42	.55	.46	52	35
31	53	64	.51	.70	48	53
32	61	87	.61	.95	57	72
38	67	79	.65	.85	61	65
44	67	67	.66	.73	61	56
46	52	77	.50	.86	47	65
$\bar{X}$	55.4	63.3	.541	.693	50.6	52.6
S^2			.01185	.02897	102.488	167.822
S			.10885	.1702	10.12367	12.9546

TABLE 22

BEAUTY CAST EXPANSION - ROOM TEMPERATURE - IMMERSED

Test #	Measured Expansion Gingival in u	Measured Expansion Pulpal in u	Percentage Expansion Gingival in %	Percentage Expansion Pulpal in %	Calculated Real Expansion Gingival in u	Calculated Real Expansion Pulpal in u
5	41	53	.40	.60	37	46
7	55	56	.53	.64	50	49
21	68	71	.65	.79	61	60
27	40	75	.39	.82	36	62
28	37	40	.36	.44	33	33
33	54	93	.52	.98	49	74
37	48	87	.46	.91	43	69
41	41	38	.40	.40	37	30
45	53	62	.52	.68	48	51
47	41	70	.39	.77	37	59
$\overline{X}$	47.8	64.5	.462	.707	43.1	53.3
S^2		344.944	.00835	.03571	76.766	206.677
S		18.30148	.09137	.18897	8.76165	14.37629

TABLE 23

BEAUTY CAST EXPANSION - 100° F - NOT IMMERSED

Test #	Measured Expansion Gingival in u	Measured Expansion Pulpal in u	Percentage Expansion Gingival in %	Percentage Expansion Pulpal in %	Calculated Real Expansion Gingival in u	Calculated Real Expansion Pulpal in u
6	60	43	.58	.46	54	35
21	45	41	.43	.43	40	33
25	48	36	.47	.39	44	29
34	53	27	.51	.30	48	22
40	59	27	.57	.29	53	22
50	21	33	.19	.35	18	26
64	36	32	.34	.35	31	26
74	35	49	.32	.53	30	40
97	40	42	.37	.45	35	34
99	42	13	.41	.14	38	10
$\bar{X}$	43.9	34.3	.419	.369	39.1	27.7
S^2		107.344	.01452	.0121	125.655	73.122
S		10.3607	.12049	.11009	11.20961	8.55115

TABLE 24

BEAUTY CAST EXPANSION - 100° F - IMMERSED

STANDARD CONDITION

Test #	Measured Expansion Gingival in u	Measured Expansion Pulpal in u	Percentage Expansion Gingival in %	Percentage Expansion Pulpal in %	Calculated Real Expansion Gingival in u	Calculated Real Expansion Pulpal in u
14	36	42	.34	.45	31	34
17	51	31	.48	.35	45	26
18	58	19	.55	.20	52	15
26	47	59	.44	.63	41	48
29	37	56	.34	.61	32	46
37	25	11	.23	.12	22	9
51	32	27	.29	.29	27	22
54	57	50	.55	.54	51	41
55	35	44	.33	.48	31	36
58	54	31	.51	.34	48	26
$\overline{X}$	43.2	35	.406	.401	38	
S^2		193.33	.01309	.02912	114.88	30.3
S		13.90443	.11441	.17064	10.71862	168.233

TABLE 25

BEAUTY CAST EXPANSION - 110° F - NOT IMMERSED

Test #	Measured Expansion Gingival in u	Measured Expansion Pulpal in u	Percentage Expansion Gingival in %	Percentage Expansion Pulpal in %	Calculated Real Expansion Gingival in u	Calculated Real Expansion Pulpal in u
1	25	62	.24	.68	22	52
12	47	34	.45	.38	42	29
13	49	21	.48	.22	44	17
17	32	27	.31	.30	29	22
19	60	72	.57	.78	54	59
20	23	24	.23	.26	21	19
29	38	56	.37	.59	34	45
34	52	57	.50	.60	47	45
35	23	30	.22	.31	20	23
40	13	10	.12	.11	11	8
$\overline{X}$	36.2	39.3	.349	.423	32.4	31.9
S^2		430.011	.02178	.0498	196.711	291.877
S		20.7367	.14758	.22315	14.02537	17.08443

TABLE 26

BEAUTY CAST EXPANSION - 110° F - IMMERSED

Test #	Measured Expansion		Percentage Expansion		Calculated Real Expansion	
	Gingival in u	Pulpal in u	Gingival in %	Pulpal in %	Gingival in u	Pulpal in u
2	6	15	.06	.16	5	12
6	30	22	.30	.23	27	17
8	29	30	.28	.34	26	25
9	51	31	.49	.34	45	25
10	24	16	.23	.18	21	13
15	39	22	.37	.24	35	18
18	86	90	.82	.96	77	73
30	51	43	.49	.44	46	33
39	32	34	.31	.35	29	26
42	42	56	.40	.64	38	48
$\overline{X}$	39	35.9	.375	.388	34.9	29
s^2		518.10	.04047	.06017	363.43	351.55
S		22.76181	.20117	.24529	19.06392	18.74981

TABLE 27

BEAUTY CAST EXPANSION - W/P .28

Test #	Measured Expansion Gingival in u	Measured Expansion Pulpal in u	Percentage Expansion Gingival in %	Percentage Expansion Pulpal in %	Calculated Real Expansion Gingival in u	Calculated Real Expansion Pulpal in u
3	42	9	.41	.10	38	7
8	54	41	.51	.45	47	34
11	57	76	.56	.78	52	59
16	37	41	.36	.44	33	33
19	49	71	.47	.78	44	59
31	45	11	.43	.12	40	8
32	55	52	.52	.57	48	43
63	45	51	.43	.54	40	41
65	56	80	.52	.86	48	66
70	65	70	.60	.74	56	56
$\bar{X}$	50.5	50.2	.481	.538	44.6	40.6
S^2		642.844	.00547	.07184	48.266	428.71
S		25.35437	.07395	.26802	6.94742	20.70534

TABLE 28

BEAUTY CAST EXPANSION - 40 SECONDS SPATULATION

Test #	Measured Expansion		Percentage Expansion		Calculated Real Expansion	
	Gingival in u	Pulpal in u	Gingival in %	Pulpal in %	Gingival in u	Pulpal in u
9	45	45	.43	.49	40	37
42	83	80	.77	.86	72	65
49	88	132	.83	1.37	78	105
67	53	12	.51	.13	47	9
68	30	51	.28	.57	26	43
73	55	38	.51	.40	47	30
75	59	91	.56	.95	52	72
78	92	52	.89	.56	83	43
84	49	63	.47	.67	44	51
89	49	56	.45	.58	42	44
$\overline{X}$	60.3	62	.57	.658	53.1	49.9
S^2		1076.4	.03837	.11446	339.877	679.877
S		32.80921	.19588	.33831	18.43577	26.07446

TABLE 29

BEAUTY CAST EXPANSION - FLUSH LINER

Test #	Measured Expansion		Percentage Expansion		Calculated Real Expansion	
	Gingival in u	Pulpal in u	Gingival in %	Pulpal in %	Gingival in u	Pulpal in u
30	29	44	.27	.47	25	36
66	31	7	.29	.07	26	5
69	45	29	.42	.32	39	24
71	1	54	.01	.59	0	44
76	16	17	.15	.18	13	13
81	26	25	.25	.27	23	20
85	34	25	.32	.26	29	20
96	31	65	.29	.69	26	52
100	17	2	.16	.02	15	1
22	2	20	.02	.22	1	16
$\bar{X}$	23.2	28.8	.218	.309	19.7	23.1
S^2		401.733	.01730	.04658	153.56	269.65
S		20.03428	.13152	.21582	12.3922	16.42119

TABLE 30

BEAUTY CAST ANALYSIS OF VARIANCE

Expansion at 500°C in Percent

Cochran's Test	at 99th percentile	
	k = 18 v = 9	C = .1741
Nine conditions, each with pulpal and gingival		C = .18433**
	k = 17 v = 9	C = .1915
Eight conditions (eliminating "40 sec. spatulation)		C = .15346 ns

9 columns (conditions)
2 rows (positions: pulpal and gingival)
10 replications per cell

Column Mean Square	.310235	F 8.9931**
Degrees of Freedom	8	
Row Mean Square	.245680	F 7.121778**
Degrees of Freedom	1	
Interaction Mean Square	.038398	F 1.113082
Degrees of Freedom	8	
Within Mean Square	.034497	
Degrees of Freedom	162	

TABLE 31

SCHEFFÉ COMPARISONS BETWEEN CONDITIONS

$$S_{\hat{\varepsilon}_L} = \sqrt{(c-1)F_{.95;\, c-1,\, N-c}MS_W \sum_{j=1}^{c} \frac{c_j^2}{n_j}} = \sqrt{(8)(2.0)(.034497)(A)}$$

where A = .03333 comparing average of 3 conditions with average of 3 other conditions $S_{\hat{\varepsilon}_L} = .136$

A = .05 comparing average of 2 conditions with average of 2 other conditions $S_{\hat{\varepsilon}_L} = .166$

$$\frac{\text{Room Not} + 100\text{ Not} + 110\text{ Not}}{3} - \frac{\text{Room Im} + 100\text{ Im} + 110\text{ Im}}{3} = \underset{\text{ns}}{.008}$$

$$\frac{\text{RoomNot+RoomIm}}{2} = .603 \quad \frac{\text{100Not+100Im}}{2} = \underline{.399 \quad \frac{\text{110Not+110Im}}{2} = .384}$$

TABLE 32

BEAUTY CAST ANALYSIS OF VARIANCE

Expansion at 500°C in Microns

Cochran's Test		at 99th percentile
		k = 18 v = 9 C = .1741
Nine conditions, each with pulpal and gingival		C = .1634 ns

9 columns (conditions)
2 rows (positions: pulpal and gingival)
10 replications per cell

Column Mean Square	2180.1375	F 9.4352**
Degrees of Freedom	8	
Row Mean Square	162.45	F .7030 ns
Degrees of Freedom	1	
Interaction Mean Square	211.0375	F .9133 ns
Degrees of Freedom	8	
Within Mean Square	231.063	
Degrees of Freedom	162	

TABLE 33

SCHEFFÉ COMPARISONS BETWEEN CONDITIONS

$S_{\hat{\sigma}_{\hat{L}}} = (8)(2.0)(231.063)(A)$

$S_{\hat{\sigma}_{\hat{L}}} = 11.10$ when comparing the average of 3 conditions with the average of 3 other conditions $n = 20$

$$\frac{\text{Room Not} + 100\text{ Not} + 110\text{ Not}}{3} - \frac{\text{Room Im} + 100\text{ Im} + 110\text{ Im}}{3} = \underset{\text{ns}}{.99}$$

$S_{\hat{\sigma}_{\hat{L}}} = 13.596$ when comparing the average of 2 with the average of 2 others

$$\frac{\text{RoomNot+RoomIm}}{2} = 49.9 \quad \frac{\text{100Not+100Im}}{2} \underbrace{= 33.77 \quad \frac{\text{110Not+110Im}}{2} = 32.0}$$

TABLE 34

SPECIFICATION TESTING - BEAUTY CAST

Percentage Expansion

	Standard Condition	W/P .28	40 Seconds Spatulation
	.47	.45	.41
	.49	.45	.42
	.49	.45	.41
	.47	.42	.48
	.44	.45	.41
	.36		
	.51		
	.42		
	.44		
$\bar{X}$	.454	.444	.426
S^2	.0021	.00018	.00093
S	.046	.013	.030
n	9	5	5

Analysis of Variance

Mean Square Between	.00126	F. 94915 ns
Degrees of Freedom	2	
Mean Square Within	.0013275	
Degrees of Freedom	16	

TABLE 35

COMBINED RESULTS - BEAUTY CAST EXPANSION in %, $\bar{X}$ and S

CONDITION	VARIABLE					
	Pulpal in Ring N=30		A.D.A. Specification Test N=19		Gingival in Ring N=30	
	$\bar{X}$	S	$\bar{X}$	S	$\bar{X}$	S
Room Temp. not Im.	.693	.17	.454	.05	.541	.11
W/P .28	.535	.27	.444	.01	.481	.07
40 Sec. Spat.	.635	.34	.426	.03	.570	.20
Col. $\bar{X}$	.6297		.4442		.5307	
S^2	.071369		.001314		.01871	

ONE WAY ANALYSIS OF VARIANCE

Between Mean Square	.20689424	F 5.9653**
Degrees of Freedom	2	
Within Mean Square	.03468335	
Degrees of Freedom	76	

SCHEFFÉ TEST FOR INDIVIDUAL COMPARISONS

$$\text{Scheffé Interval} = \sqrt{(r-1)F_{.95;\ r-1,\ N-r}\, MS_W \left(\frac{1}{n_1} + \frac{1}{n_2}\right)}$$

$= .1366$ for $n_1 = 30$ $n_2 = 19$

$= .120$ for $n_1 = 30$ $n_2 = 30$

$\bar{X}$	Pulpal in ring	Gingival in ring	A.D.A. Spec. Test
	.6297	.5307	.4442

$\underline{.6297 \qquad .5307}$

$n_1 = 30$
$n_2 = 30$

$\underline{.5307 \qquad .4442}$

$n_1 = 19$
$n_2 = 30$

APPENDIX C

X-Ray Technique Plates

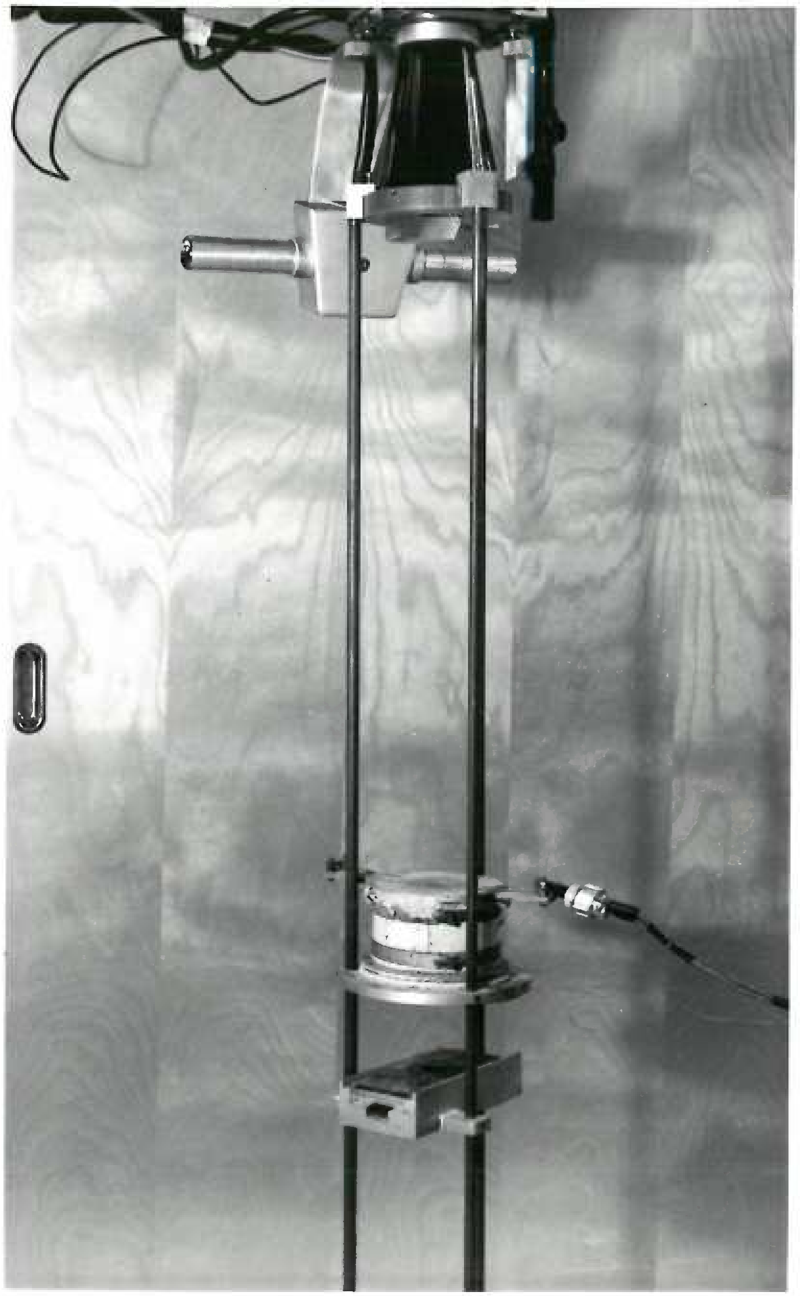

PLATE 1. Fixture For X-Ray Technique

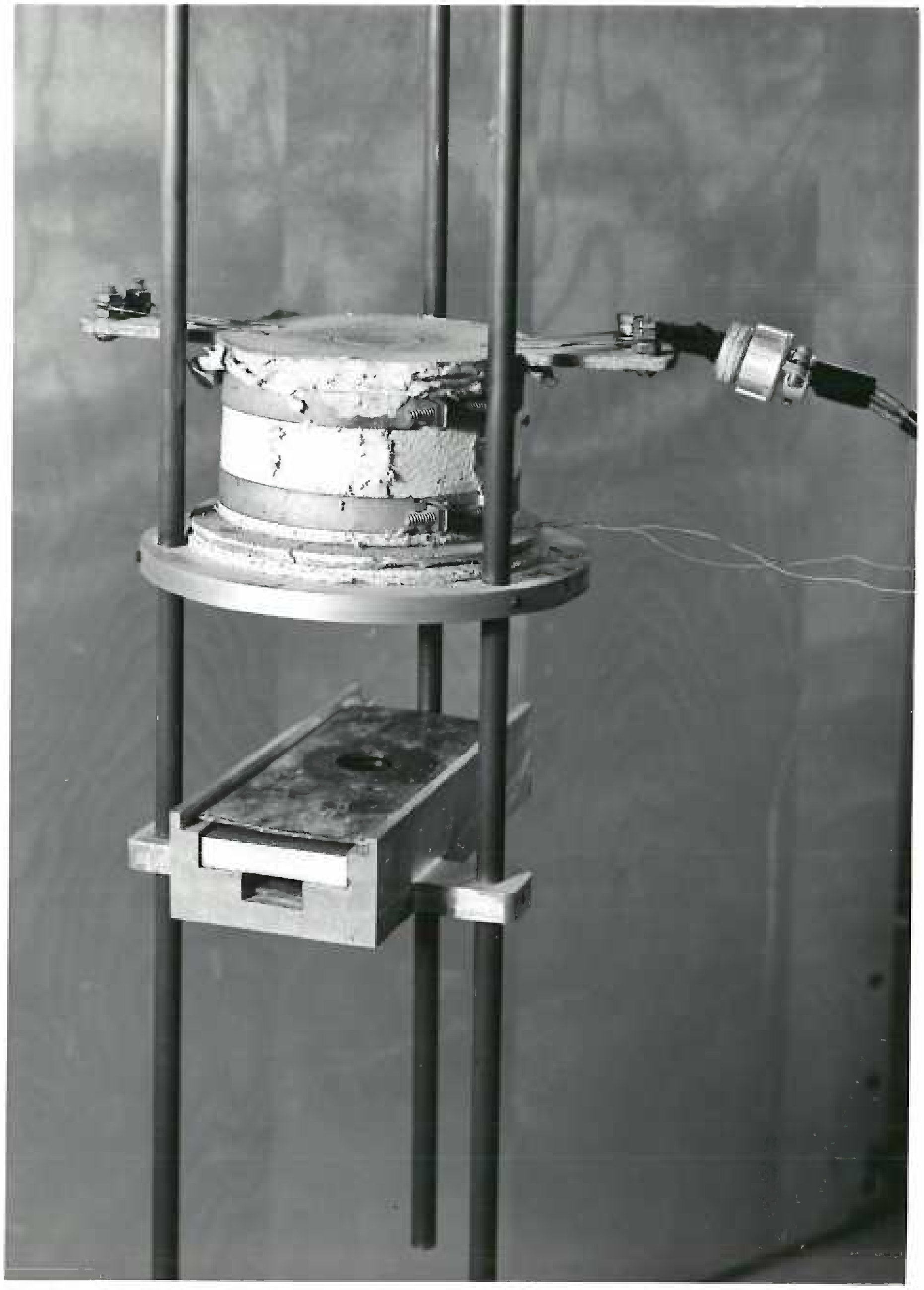

PLATE 2. Oven And Cassette

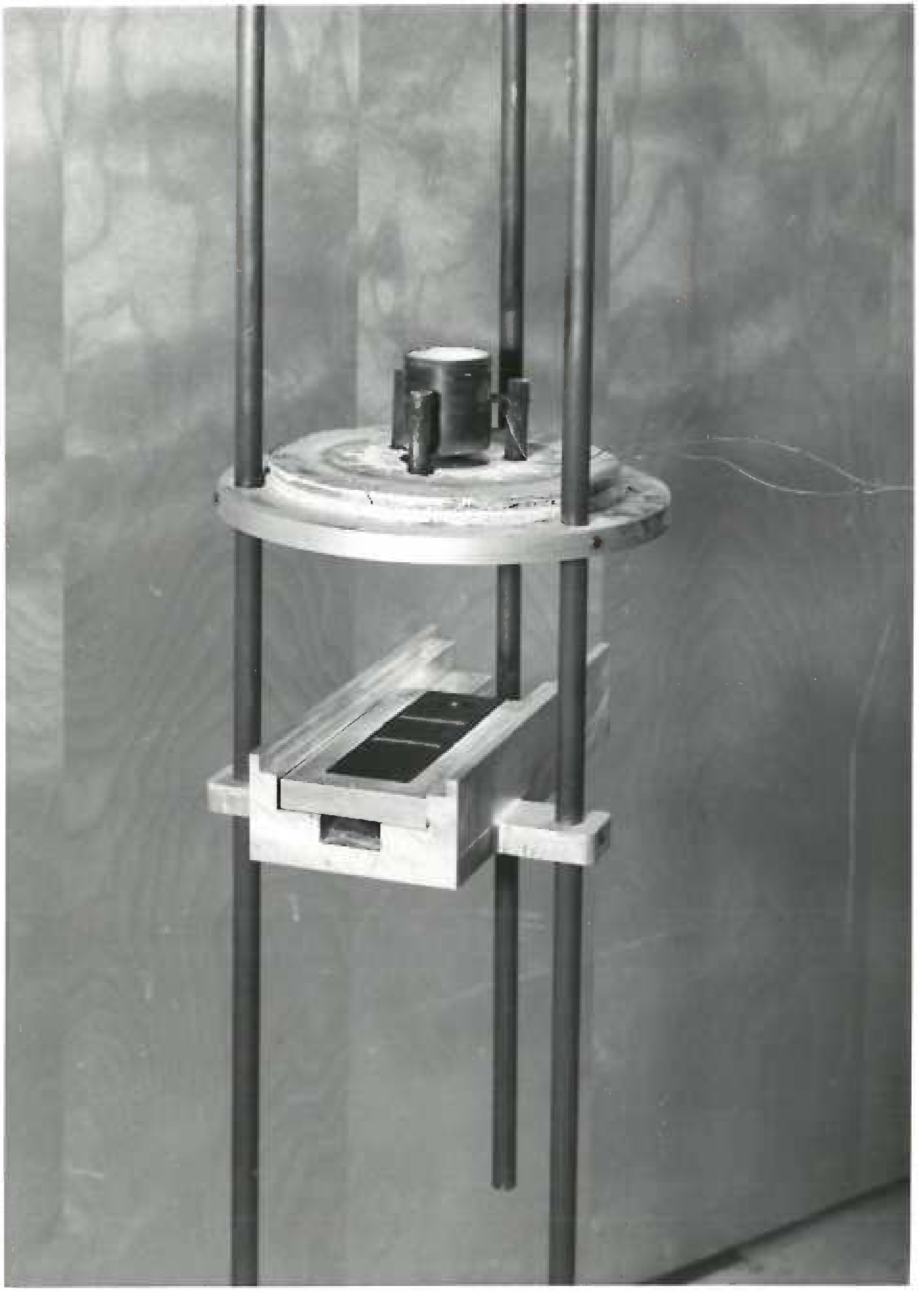

PLATE 3. Oven Platform, Mounted Ring,

Cassette In Place