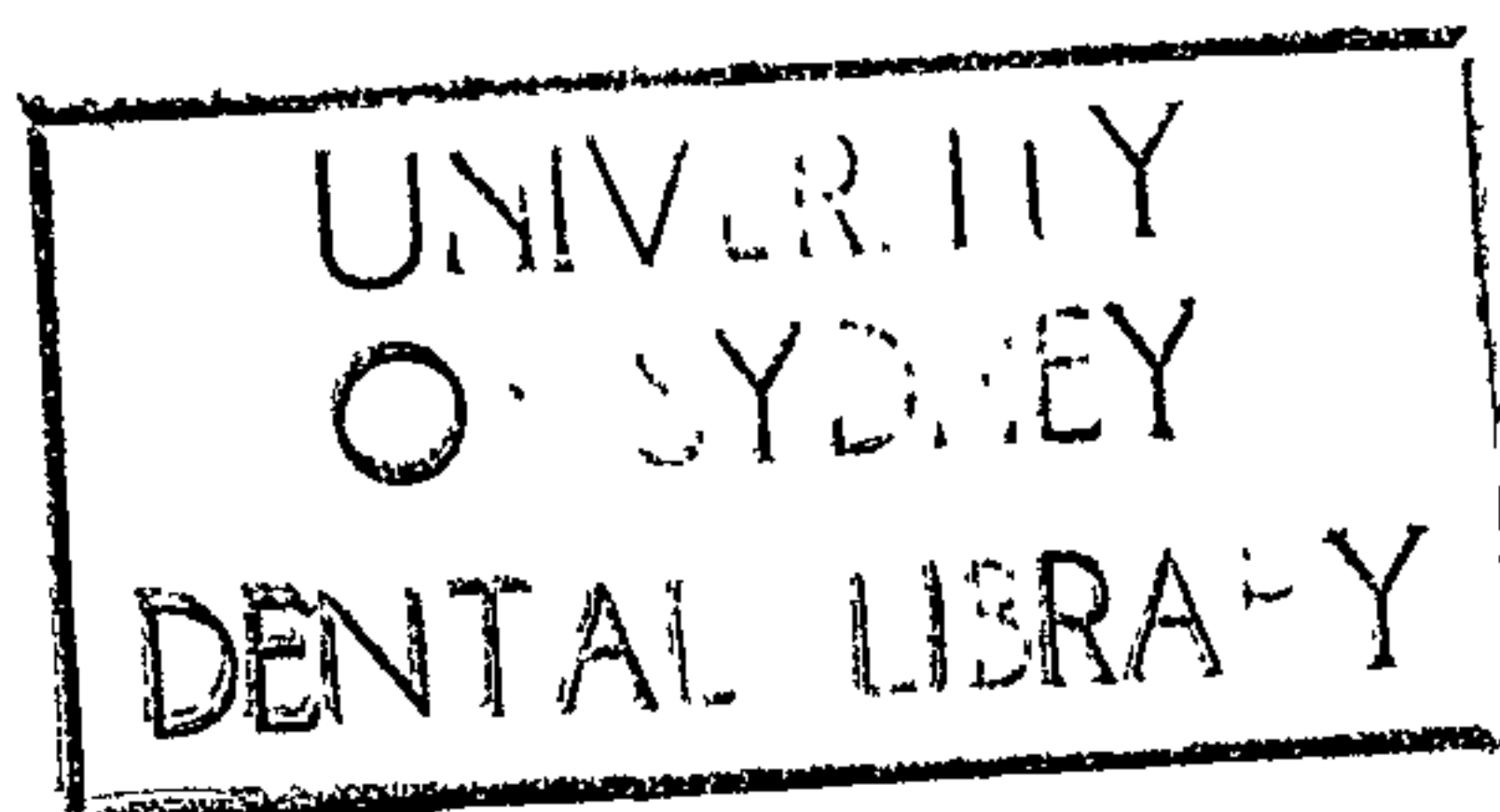


THE EFFECT OF CASTING RING LINERS ON THE  
DIMENSIONAL ACCURACY OF FULL CROWN CASTINGS

Erica Frances Morey, B.D.S.

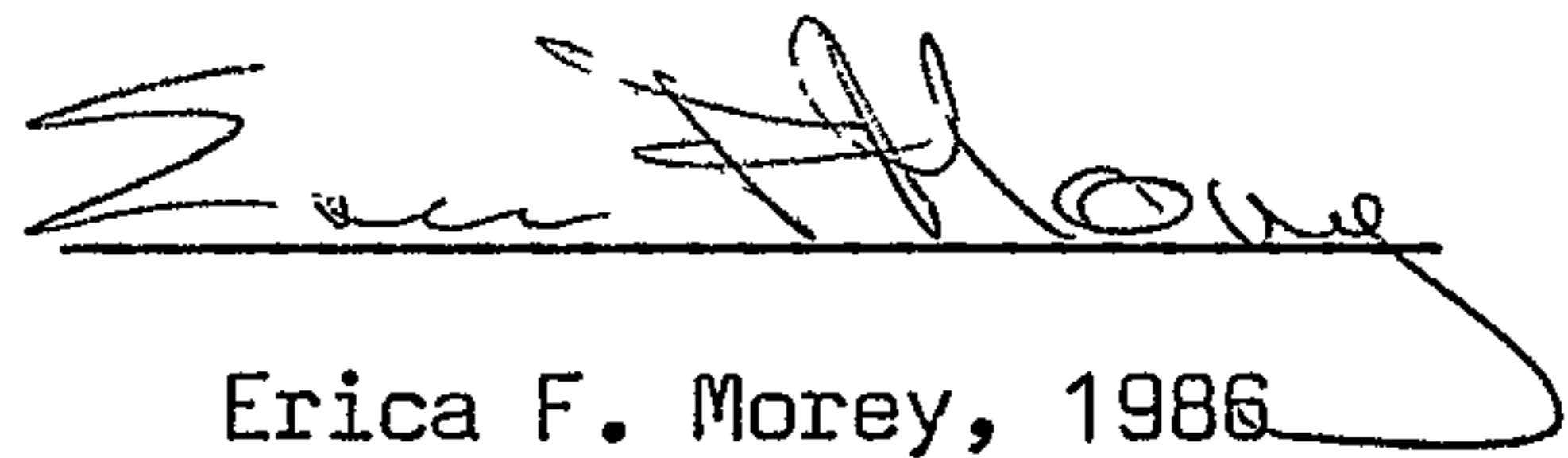
Thesis submitted for  
the degree of Master of Dental Surgery



Department of Operative Dentistry,  
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University of Sydney.

Candidate's Certificate

This is to certify that the work presented in this thesis was carried out by the candidate in the Faculty of Dentistry, University of Sydney, and has not been submitted to any other university or institution for a higher degree.

  
Erica F. Morey, 1986

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This thesis is dedicated to my father  
who will always be

"lucerna pedibus meis"

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## CHAPTER ONE

### LITERATURE REVIEW

#### 1.1 INTRODUCTION

Casting is one of the most widely used methods for the fabrication of dental restorations outside the mouth (Phillips, 1982a). The ultimate assessment of cast gold dental restorations lies in the accuracy of fit of the casting and its duplication of tooth structure (Palmer, Roydhouse and Skinner, 1961). The procedure is complex and involves a series of stages, each of which may affect the dimensions and therefore accuracy of fit of the final product.

These steps are:

- making a wax pattern which is a replica of the missing tooth structure;
- embedding the pattern in an investment which is essentially a mixture of binder (such as calcium sulphate hemihydrate) and silica, mixed with water;
- removing the wax from the hardened investment and forcing molten alloy into the space left by the wax pattern.

Inlay waxes contract on cooling and tend to distort.

Investments expand when setting, expand more if exposed to water during setting and expand when heated. Casting alloys contract when cooling from liquidus to room temperature.

Therefore the dimensional accuracy of the casting depends not only on the methods used but also on the various materials involved in its construction. Clinical observation and extensive research have shown that cast restorations show large variations in accuracy of fit when returned to their preparations.

This review will deal with the validity of these various observations and will examine the implications of their conclusions concerning the accuracy of the "lost-wax" casting process.

## 1.2 HISTORY OF THE CAST RESTORATION

Metal castings were not produced until about 3000 B.C. when copper was cast in Mesopotamia. The art of casting was later introduced into Egypt where the "lost-wax moulding process" was first developed (Weinberger, 1948a; Anon., 1982).

The most ancient dental prosthesis, fabricated from gold wire, was found in Egypt and dated as far back as 2500 B.C. (Weinberger, 1948a). In approximately 500 B.C. the Etruscans produced bridges made of soldered gold bands. This technique was adopted and further developed by the Romans. After the fall of the Roman Empire, the art of dental prosthetics completely disappeared in Europe until the eighteenth century (Roberts, 1973).

However, foundry practice flourished in the Far East. The Chinese developed specific bronze alloys and made elaborate use of

the lost-wax process to produce artistic metal castings of remarkable quality and intricacy of design (Hollenback, 1962; Anon., 1982).

One of the Renaissance craftsmen, the sculptor Benvenuto Cellini, (1500 - 1571), in his autobiography, described his method of casting in both gold and bronze. He coated his finely detailed wax model with a reinforced refractory shell. This was heated to eliminate the wax and molten metal was then poured into the mould cavity (Shell, 1960; Hollenback, 1962).

The oldest dental castings were gold inlays found in the teeth of the natives of Ecuador dating around the first century A.D. (Weinberger, 1948b). Decorative inlays of various materials were also found in the teeth of the pre-Columbian Indians (de la Borbolla, 1940; Alexanderson, 1940). The Aztecs and Mayas are known to have made gold castings before the time of Cortez, in moulds probably made from clay or possibly from plaster of Paris, from which the wax was melted (Shell, 1960).

After the discovery of dental cement (oxychloride of zinc) in 1860 (Bremner, 1939), various materials were used for the construction of dental inlays. These included pieces of porcelain ground to fit the cavity in an attempt to overcome the aesthetic problems of the popular gold foil fillings. Another method was to burnish platinum or a pure gold matrix to the cavity and fill this with gold solder, or a combination of gold foil and solder.

In 1897, Philbrook read his famous paper entitled "Cast Fillings" (Bremner, 1939; Hollenback, 1962). He described a method

of casting Watts metal into a mould formed from a wax pattern for the restoration of posterior teeth. However this technique was soon abandoned because of the inadequacy of the cementing medium.

In 1903, Lentz cast occlusal surfaces to banded gold crowns by the lost wax method of mould formation (Hollenback, 1962; 1964), but apparently did not apply his knowledge to the fabrication of cast inlays.

It was W.H. Taggart who, in 1907, finally described a casting process which launched the cast restoration as it is known today. His process was to take a wax pattern of the lost tooth structure, invest it, heat the investment to remove the wax, and cast gold into the space formed using air pressure. Taggart's investment had the following formula: plaster of Paris 37.5 per cent, silica 57.5 per cent and graphite 5 per cent. Its properties were a setting expansion of 0.45 per cent, hygroscopic expansion of about 1 per cent and a thermal expansion of 0.77 per cent (Shell, 1960).

While his methods were both revolutionary and sound, Taggart was unable to overcome the problem of casting shrinkage which resulted in restorations which were undersize (Hollenback, 1962). He mistakenly believed that applying air pressure would prevent alloy shrinkage and his investment did not provide sufficient mould expansion and therefore compensation at the temperatures he used, probably because no casting ring liner was used in the ring to allow effective investment expansion.

Since that time extensive research has been carried out to establish a scientific basis for the production of dimensionally accurate cast restorations. Lane (1909c) became convinced that all castings made by the Taggart method were undersize and attributed this to the shrinkage of gold. As a result, Lane conceived the idea of casting into an enlarged mould and he achieved this using an investment containing a high percentage of silica (approximately 75 per cent), plus plaster of Paris, heated to about 650°C. Knowing that a high silica content investment showed considerable thermal expansion, he was the first to introduce mould expansion as a compensation technique to the dental casting process (Hollenback, 1962).

In 1910, Van Horn introduced a different method of compensation. He recommended that the wax pattern be invested at a temperature equal to mouth temperature. He stated that the resultant wax expansion and available investment expansion must, either singly or in combination, compensate for alloy contraction. Van Horn achieved this by mixing a high silica content investment with warm water (46°C) and after the pattern was invested placed the sealed inlay ring in a water bath held at 43°C until the investment had set. Access of water to the setting investment was prevented; the water bath was used only as a convenient way of maintaining the required temperature of the wax pattern and the investment. While not attempting to determine the amount of expansion needed, Van Horn made a great contribution to the accuracy of dental casting by the "expanded pattern" technique.

In the following year, Price, in his classical experiment using a vitreous silica mould, determined a value of 1.64 per cent linear contraction for pure gold as it changed from the liquid to the solid state at a constant temperature of 1064°C and a 2.2 per cent linear contraction from this freezing point to room temperature. He concluded that all the contraction of the gold except that which occurred after the metal had solidified was compensated for by the addition of liquid gold from the crucible. However it should be noted that his apparatus did not simulate dental casting conditions.

Many years elapsed before any further fundamental contributions were made to the art of dental casting. During this time operators argued over whether casting should be done as soon as the wax was eliminated by the rapid boil out technique or the high temperature furnace burn-out method, as against cooling to room temperature after elimination of the wax before casting (Shell, 1960). These operators did not appreciate that the investment contracted upon cooling.

The low heat casting technique was finally abandoned in 1928 when Coleman published his famous Research Paper No.32 for the U.S. National Bureau of Standards, in which he detailed the great shrinkage which occurs upon cooling investment after heating. This paper also gave a number of formulae for dental investments available at the time, in which the proportion of plaster of Paris varied from 19 to 56 per cent, the balance being quartz, some graphite, colouring material and in some cases boric acid. Weinstein (1929) found that adding boric acid to customary investment mixtures prevented the shrinkage which occurred when investments were heated to about 370°C and that with the addition of this chemical, quartz based investments

expanded approximately 0.9 per cent when heated to 700°C (Shell, 1960). Later, Moore (1933) discovered that by the addition of chlorides to investments he could obtain a thermal expansion of as much as 1.1 per cent from a quartz based investment.

Two important discoveries were made in the next few years; the use of cristobalite in investment, and the hygroscopic setting expansion technique.

A number of authors (Taylor, Paffenbarger and Sweeney, 1930; Sweeney, 1933) studied the use of cristobalite as a refractory in dental casting investments and found that a cristobalite based investment (75 per cent cristobalite, 25 per cent plaster) heated to temperatures between 400°C and 800°C produced dimensionally accurate castings.

D.W. Phillips (1935) further refined this technique by the use of a "control powder" mixed with a cristobalite investment in varying proportions, designed to give different thermal expansions to the investment.

In 1932 Scheu presented a new technique which used the setting expansion of investment to compensate totally for gold alloy shrinkage. He found that if the invested pattern were placed in water after its initial set (about ten minutes) there would be sufficient expansion to compensate for gold shrinkage. He also stated that greater expansion was achieved with a thicker mix and recommended that the investment remain in the water bath for between 20 and 30 minutes. Scheu described his recommendations as being radically

different from those accepted at the time; he had in fact discovered the hygroscopic setting expansion technique for dental investments.

Although Scheu was the first to use this technique deliberately for compensation, this form of expansion was in fact being used unintentionally after the introduction of the wet asbestos liner.

Dr. Wilmer Souder recognised that the thermal expansion of the investment would be greatly inhibited by the rigid metal casting ring which had a lower thermal expansion. He advocated fitting the ring with a soft asbestos liner to act as a heat resisting cushion which would permit the investment to undergo its full thermal expansion (Hollenback, 1962; 1964). It has since been established (Scheu, 1935) that whether used wet or dry the asbestos liner definitely produces hygroscopic expansion of the investment but of an undetermined amount (Shell, 1960).

"Inlay casting is an intricate process and probably always will be so, as all the materials used in the process are subject to volumetric change" (Volland and Paffenbarger, 1932); nevertheless, it can be seen that great advances have been made in the dental casting process since 1907, to develop Taggart's almost artistic innovation into a more precise science.

### 1.3 THE THEORY OF COMPENSATION

The concept of compensation for the shrinkage of wax and gold by investment expansion came into being in the early 1920s when

Weinstein and Coleman at the U.S. National Bureau of Standards scientifically evaluated the three materials used in the production of a dental casting (Hollenback and Shell, 1965). Many researchers have since attempted to prove that theoretically, if the shrinkages of the wax and gold alloy are known, the mould can be expanded an equal amount thus solving the problem of compensation (Phillips, 1982d).

In the construction of the cast gold restoration all the materials used exhibit dimensional change. However, in order to fulfil its function, a cast restoration must have a high degree of accuracy. The ideal cast restoration should be one where the cementing medium is small in amount, especially at the margins (Jørgensen, 1960a, 1960b).

The problem of accuracy of the casting and compensation for wax and alloy shrinkage is further complicated by the need for the inlay or internal restoration to be slightly undersize to provide space for the minimum amount of cementing medium allowable while still exhibiting dimensional adaptation to the cavity; on the other hand, for the same reason, the external or crown restoration should be slightly oversize. In the case of an MOD casting, the requirements are even more complex, as its fit in the tooth preparation involves both internal and external surfaces.

### 1.3.1 Methods of Compensation

Compensation for the shrinkages of both wax and gold alloy which are inherent in the casting process may be obtained by any one or a combination of the following four methods. These are:

- 1) thermal expansion of the wax pattern;
- 2) setting expansion of the investment;
- 3) an enhanced setting expansion of the investment in the presence of additional water: commonly known as hygroscopic expansion;
- 4) thermal expansion of the investment.

Thermal expansion of the wax pattern can be obtained by maintaining the temperature of the water-investment mixture at approximately 40°C to 42°C after the pattern has been invested and before the investment sets. However, such a treatment will produce stress relief of the wax with consequent distortion and for this reason this technique is not recommended (Coleman, 1926; Hollenback and Rhoads, 1960a).

The two methods of compensation currently used are commonly known as the thermal expansion technique and the hygroscopic expansion technique.

In the first, sometimes called the "high heat" technique, it is usually stated that the major contribution to mould expansion is provided by thermal expansion of the investment which occurs when it is heated to a burn-out temperature of 650 - 700°C. Investments designed for this technique have a high thermal expansion at such temperatures, and under usual methods of laboratory measurement show a relatively small setting expansion. Recent measurements of setting expansion of such investments however, show that when setting in contact with a wetted casting ring liner the setting expansion can be as high as, or higher than, the thermal expansion (Jones and Wilson, 1970; Earnshaw 1978, 1982).

In the second, sometimes called the "low heat" technique, the moulds are heated to temperatures of only 480 - 500°C. At these temperatures the investments used have low thermal expansions, but high setting expansions are obtained by exposing the setting investment to additional water, so invoking the so-called "hygroscopic expansion" effect.

In many hygroscopic expansion techniques the unset investment mould is immersed in a water bath held at 38°C. Raising the temperature above ambient usually slightly lowers the observed hygroscopic setting expansion (Earnshaw, 1969a); the intention is to soften the wax pattern enough to reduce its restraint to the setting expansion of the investment. Of course, this also invokes thermal expansion of the pattern as an additional compensatory mechanism.

#### 1.4 THE WAX PATTERN

The first step in the inlay casting process is the fabrication of an accurate wax pattern. Dental inlay casting wax is used either in the mouth by the direct technique or at room temperature on a die in the indirect technique.

Typical constituents of an inlay wax may include paraffin wax (generally the main ingredient), carnauba wax, beeswax, ceresin wax, candelilla wax, gum dammar resin, synthetic waxes and some colouring material (Craig, 1985b). With the exception of synthetic waxes, all these substances are of natural origin, derived from mineral or vegetable sources. Paraffin wax is derived from the high-boiling

fractions of petroleum and can be obtained in different grades with softening temperatures varying over a wide range, depending upon the molecular weight and distribution of the constituents. In contrast, synthetic waxes have a high melting point and are incorporated to improve important manipulative properties of the wax. Control of these properties is therefore accomplished by a combination of factors which include the amount of the different waxes present, their melting ranges and the presence of resin (Craig, Eick and Peyton, 1965, 1966, 1967; Ohashi and Paffenbarger, 1966; Craig, Powers and Peyton, 1971).

Waxes are low molecular weight linear polymers which may be crystalline or amorphous. They have some important physical properties typical of linear polymers which affect their manipulation (Moskowitz, 1978).

They have a very high thermal expansion and contraction, in fact the highest of all dental materials, with coefficients of linear thermal expansion typically in the range of  $300 - 600 \times 10^{-6}/K$  (Darvell, 1983). Thus temperature changes occurring during manipulation of inlay wax (for example, cooling from mouth temperature to room temperature) are a potential source of dimensional inaccuracy in wax patterns. If the pattern is physically unrestricted when cooling, as in the case of a direct wax pattern removed from the mouth, a uniform linear thermal contraction can be expected. Moreover if any thermal contraction is prevented by physical restraint, as when the pattern cools on a tooth from the wax softening temperature to mouth temperature, or cools on a die from the wax softening temperature to ambient temperature, residual stresses will be set up in the wax and

these can lead to subsequent distortion by stress relief (Maves, 1932; Lasater, 1940; Phillips and Biggs, 1950; Hollenback and Rhoads, 1959a, 1959b; Fusayama, 1959a).

Waxes exhibit visco-elastic behaviour under load, and service temperatures (ambient and mouth) are close to their melting temperatures; thus their mechanical properties are markedly temperature dependent and time dependent. Elastic moduli are low (for example, a typical inlay wax has a Young's modulus in compression of only about 1,000 MPa) (Darvell, 1983), so that resistance to deformation is poor.

Visco-elastic behaviour of waxes makes them susceptible both to stress relief and relaxation, as residual stresses induced during manipulation of the wax disappear. Stress relief is the time-dependent reduction of residual stresses, manifested as a delayed elastic recovery ("elastic memory"), which produces a corresponding distortion. If the pattern is physically unconfined this is the normal way in which residual stresses disappear. The rate at which stress relief occurs is highly temperature dependent and may be greatly reduced by cooling the wax pattern to temperatures below ambient. Thus if wax patterns must be stored before investing, it is sometimes recommended that this be done in a refrigerator (Moskowitz, 1978; Craig, O'Brien and Powers, 1983). The pattern should be allowed to return to ambient temperature before investing.

On the other hand, stress relaxation involves a time-dependent decrease in applied or residual stress by plastic deformation (creep or "flow"), so that here residual stresses disappear without an

accompanying distortion. If the pattern is physically confined, for example a full crown pattern left on the die, this is the only way that residual stresses can disappear (Sumii, 1971).

The American Dental Association Specification (1974) for dental inlay casting wax classifies these materials into three types: Type A (hard), Type B (medium) and Type C (soft) and recommends that Type B is a direct technique wax to be used for making patterns in or out of the mouth and Type C wax is an indirect technique wax suitable only for the production of inlays and crowns outside the mouth.

The difference between Types B and C waxes lies partly in the permissible amount of plastic deformation at specified temperatures. This property of dental waxes is influenced by the presence of solid-solid and melting transformations which occur in the various component waxes and is a function of temperature (Powers, Craig and Peyton, 1969). Annealing wax at 50°C for 24 hours has the effect of increasing the resistance of the wax to penetration and distortion (Markley, 1958; Sumii, 1971; Powers and Craig, 1974).

Ideally inlay waxes for direct patterns should have minimum flow at 37°C and relatively high flow a few degrees above mouth temperature (approximately 45°C) so that the wax is in a plastic condition while not being uncomfortably hot in the mouth. Type B inlay wax is permitted a maximum flow of one per cent at 37°C to ensure that carving and removal of the pattern from the mouth can take place without distortion, and Types B and C waxes must have a minimum flow of 70 per cent at 46°C and 43°C respectively.

#### 1.4.1 Contraction of Inlay Wax

The amount of contraction which inlay waxes undergo from mouth temperature to room temperature is of particular interest when the direct technique is used to form a wax pattern. Phillips (1982b) stated that the average linear coefficient of thermal expansion over such a temperature range was  $350 \times 10^{-6}/K$  and therefore the average contraction in this range was 0.35 per cent. Many other authors have quoted figures for wax shrinkage over this temperature range and these have varied from 0.3 per cent to 2.3 per cent, although much of this research was not carried out using simulated dental conditions.

In 1910, Van Horn recognised that wax patterns were not constant in their dimensions under varying thermal conditions. He measured a specimen of Taggart's pattern wax at body temperature and again at the temperature of the water used to mix the investment ( $13^{\circ}C$ ) and recorded a linear contraction of 0.52 per cent.

Coleman (1926, 1928) used an experimental wax of 60 per cent paraffin, 25 per cent carnauba wax, 10 per cent ceresin wax, 5 per cent refined beeswax and a small amount of oil-soluble colouring material and reported a thermal expansion of 0.72 per cent between  $25^{\circ}C$  and  $40^{\circ}C$  (average coefficient of  $600 \times 10^{-6}/K$ ). Four commercial waxes were also measured over this temperature range and exhibited expansions varying from 0.70 per cent to 0.83 per cent.

However, a phenomenon of particular importance in any wax expansion compensation technique is the varying coefficient of thermal expansion over different temperature ranges. Paffenbarger and Sweeney (1931) quoted, for a commercial inlay wax, a linear

expansion of approximately 0.22 per cent between 18°C and 28°C; 0.34 per cent between 28°C and 38°C; and 0.5 per cent between 38°C and 48°C. As the expansion in the highest range (38°C to 48°C) was almost double that in the lowest range (18°C to 28°C) these facts must be carefully considered in the use of a wax expansion compensation technique.

Goldberg (1937) tested three commercial waxes for shrinkage from mouth temperature to room temperature (27°C). The three waxes showed contractions of 0.38 per cent, 0.2 per cent and 0.1 per cent, which indicated the large range of shrinkage inherent in different wax types. Goldberg recommended the use of the wax with 0.1 per cent contraction for the direct technique and the wax with 0.38 per cent contraction for patterns made on a die at room temperature in the indirect technique.

Scheu (1937) observed that when medium-hard inlay wax was heated to the lowest temperature that would permit manipulation and held under pressure in the cavity during cooling, it contracted an average of 0.4 per cent. When a hard wax (in a semi-liquid state) was used, the shrinkage was 0.6 per cent to 0.8 per cent and patterns made by forcing liquid wax into the cavity with a syringe showed a contraction as great as 1.6 per cent. Scheu recommended that wax should therefore be warmed, preferably in warm water to the lowest temperature that would permit easy manipulation to minimise the amount of subsequent shrinkage.

Souder and Paffenbarger (1942c) stated that over the temperature ranges commonly used in inlay techniques a shrinkage of

0.7  $\pm$  0.2 per cent was common for commercial waxes and 0.5 per cent was typical for an inlay wax which according to the American Dental Association Specification for inlay wax (1974) would be classified as a medium type. These authors stated that "it is important to know the exact contraction of the wax pattern from mouth to room temperature so that it can be allowed for in devising a feasible technic where one wishes to cast a restoration to an exact dimension."

Fusayama (1959a) made an extensive study of the behaviour of pattern wax under simulated dental conditions. He observed that wax moulded into a cavity would exhibit both shrinkage during solidification and cooling shrinkage after solidification. He examined the thermal behaviour of molten wax which is often used in forming patterns in the indirect technique. Fusayama concluded that the total contraction was much larger than the thermal shrinkage that occurs after solidification alone and stated that the unrestricted thermal shrinkage of wax from the softening point to room temperature was 0.9 per cent. He noted that while the cavity walls would resist these shrinkages to some extent, they occurred not only after removal from the steel dies used in his study but even in the cavities before removal. Fusayama also stated that the shrinkage of inlay wax could not be overcome by applied pressure during solidification on a room temperature die.

Hollenback and Rhoads (1960a) studied the effect of a number of factors and manipulative variables on the thermal expansion of inlay waxes. They found that the greatest degree of expansion and most

consistent values were obtained when indirect wax patterns were formed under high pressure (300 lb/in<sup>2</sup>).

In 1965, Craig, Eick and Peyton made an extensive study of the properties of waxes. Results were given for two inlay waxes as well as a number of mineral, insect and plant waxes. Kerr hard wax (blue) possessed three linear rates of expansion;  $(323 \pm 2) \times 10^{-6}/K$  (from 22.0°C to 37.5°C),  $(629 \pm 22) \times 10^{-6}/K$  (37.5°C to 45.0°C) and  $(328 \pm 43) \times 10^{-6}/K$  (45.0°C to 50.0°C). Figures obtained for Kerr regular wax (blue) were  $(263 \pm 6) \times 10^{-6}/K$  (22.0°C to 32.7°C),  $(662 \pm 42) \times 10^{-6}/K$  (32.7°C to 40.9°C) and  $(458 \pm 50) \times 10^{-6}/K$  (40.9°C to 46.9°C). The authors suggested that these varying rates of expansion for inlay waxes were observed because the ingredient waxes were undergoing second-order transitions at different temperatures.

In the following year, Ohashi and Paffenbarger reported average coefficients of thermal expansion over the range of 25°C to 37°C of  $240 \times 10^{-6}/K$  for a Type B inlay wax and  $530 \times 10^{-6}/K$  for a Type C wax. These figures are equal to an expansion of 0.29 per cent for a Type B wax and 0.64 per cent for a Type C inlay wax.

Thus it can be seen that a large and confusing range of values has been quoted for the thermal expansion of inlay waxes. The American Dental Association Specification for inlay wax (1974) imposes a maximum of 0.2 per cent linear expansion for a Type B inlay wax when heated from 25°C to 30°C and a maximum of 0.6 per cent over the temperature range 25°C to 37°C.

#### 1.4.2 Distortion of Wax Patterns

Distortion of wax patterns always accompanies stress relief, and this process is accelerated by increased temperature. Although this is not really a dimensional change which requires compensation, it is an important factor which must be considered in any techniques which involve heating the wax pattern before the investment has fully set. Such techniques obviously include the "expanded pattern technique" introduced by Van Horn in 1910 and the hygroscopic investment expansion technique advocated by Scheu (1932) where warm water (38°C) was used for the investment mix and immersion of the investment material during setting.

Factors which influence wax pattern distortion have been thoroughly investigated by a number of workers (Maves, 1932; Lasater, 1940; Phillips and Biggs, 1950).

Maves (1932) presented data from numerous experiments on wax patterns and found that all inlay waxes become distorted when subjected to changes of temperature, the distortions varying in proportion to the degree of heat applied. He also observed that melted wax which was poured into the mould and allowed to cool without pressure showed the least distortion when heat was reapplied and concluded that poured patterns distorted less than those formed by manipulation of the wax. Maves recommended that for compensation in the casting procedure one should not depend on wax expansion which would result in distortion but rather on a standardised setting and thermal expansion of the investment.

In 1955, Smyd stated that wax patterns possessed "elastic memory", shown by a tendency to revert to their original form after being worked or changed in shape. This of course is a manifestation of delayed elastic recovery (i.e., stress relief). Smyd explained that the distortion was caused by the relief of stresses produced in a thermoplastic medium such as wax during the carving of a pattern when the wax was subjected alternatively to compression, tension and shear stresses and that these stresses were relieved in the form of distortion at temperatures lower than the forming temperature of the pattern. Smyd also noted that while stresses are dissipated on melting of the wax, the use of molten wax does not necessarily produce a stress free pattern, as stresses will be induced during cooling, even when the wax is subjected to pressure, because of restraint to thermal contraction exerted by the preparation.

Phillips and Biggs (1950) investigated the effect of temperature of wax manipulation and storage temperature on the distortion of over 400 wax patterns. They found that most of the distortion occurred during the first two to three hours of storage off the preparation and in some patterns in the first 30 minutes. Distortion was more pronounced as the storage temperature was increased and also in patterns which had been formed from moulded wax at non-uniform temperatures and which had been subjected to patching and pooling during formation. These authors recommended a low storage temperature to minimise distortion and also recommended that ideally patterns should be invested immediately after removal from the preparation.

Fusayama (1959a) studied dimensional changes and distortion of four simulated dental patterns (Class V, MOD, full crown and Class I patterns) using a Type B (medium) wax and a soft paraffin wax. The three moulding techniques employed were softened wax allowed to cool under heavy pressure and fluid wax hardened with and without applied pressure. He observed that soft paraffin wax produced patterns of much greater accuracy than inlay wax on the dies at room temperature, which would be expected since the range from manipulating temperature to room temperature is much smaller for paraffin wax. He stated that the manipulation temperature of the wax should be only slightly above the temperature of the cavity in which it is moulded and that the press moulding technique produced the most accurate patterns while the other two techniques using melted wax resulted in greater shrinkage. Fusayama suggested that this finding, which was quite different from those of Maves (1932) and Souder and Paffenbarger (1942c) could result from the fact that shrinkage occurring during solidification of the wax would be much larger than its subsequent thermal contraction, and that resistance by the cavity walls resulted in severe residual stresses in the wax pattern, with subsequent slow and continuous shrinkage and distortion.

Hollenback and Rhoads (1959a) investigated the behaviour of inlay wax patterns when subjected to varying storage temperatures and lapses of time. They concluded that provided the wax was thoroughly softened before adaptation to a cavity, the resulting patterns showed a relatively small distortion even when subjected to elevated storage temperatures for extended periods (45°C for 48 hours). They also observed dimensional changes in a typical MOD wax pattern and concluded that clinically insignificant changes occurred where the

wax was deliberately deformed by pressure during adaptation to the cavity. Hollenback and Rhoads summarised their findings by stating that wax patterns had been unjustly accused of being a major cause of dimensional error in the casting process and that inlay waxes were comparatively stable materials if not mistreated during pattern formation or stored for prolonged periods at elevated temperatures. This finding was a direct contradiction to most of the results published previously in this field of research.

More recently Meiners and Kunzemann (1983) and Jørgensen and Ono (1984) attempted to evaluate the effect of the type of wax, the thickness of the pattern, the method of wax manipulation and the effect of storage time on the distortion of full crown patterns. They concluded that because of the inherent property of distortion, inlay wax was an inadequate material for pattern production in techniques requiring high precision.

Distortion by stress relief is a function of the length of time during which the pattern is stored and is also influenced by the temperature at which the pattern is stored and any changes of temperature to which the pattern is subjected after it is formed. The longer the wax pattern is allowed to remain off the preparation before being invested, the greater is the release of residual stress. Since higher temperatures raise the flow and lower the yield point of wax, the release of stress is accelerated by increases in either storage temperature or investing temperature.

## 1.5 GOLD ALLOY SHRINKAGE

When a molten metal or an alloy is cast a volumetric contraction occurs when the metal cools from the melt temperature to ambient temperature. It should be noted that pure metals have a single freezing temperature while most alloys freeze over a temperature range, which is the interval between the liquidus and solidus temperatures.

Contraction occurs both during cooling of the liquid metal and during solidification; however feeding of additional molten alloy from the sprue, reservoir or button has been shown to compensate fully for the shrinkage of the alloy during these two stages (Price, 1911; Coleman, 1928; Souder and Paffenbarger, 1942a).

It is generally accepted that the observed linear casting shrinkage of an alloy is simply the thermal contraction which occurs when the solidified casting cools from its solidus temperature to ambient temperature. It is this casting shrinkage which requires compensation by investment expansion.

Coleman used the expression "casting shrinkage" to include the contraction which occurred during all the three stages already described and employed the term "net casting shrinkage" to describe the casting contraction measured in his experiments. Others have used the term "casting shrinkage" to describe the measured contraction of the alloy which occurred during casting (Hollenback and Skinner, 1946).

Earnshaw (1957, 1958) suggested the following nomenclature as there was no clear precise meaning for the term "casting shrinkage":

- a) **Inherent Casting Shrinkage:** the maximum contraction that could occur during the casting of a given alloy. This would equal the unrestricted thermal contraction of the alloy when cooling from its solidus temperature to ambient temperature.
- b) **Actual Casting Shrinkage:** the contraction of the alloy which does occur when a casting is made. This dimensional change can also be described as the "observed" or "measured" casting shrinkage.
- c) **Net Casting Shrinkage:** the difference between the compensation provided by the available investment expansion and the actual casting shrinkage of the alloy. This last term describes the amount by which the final casting differs in size from the original wax pattern.

Since it is possible that castings may be either oversize or undersize, a better term would be "discrepancy" or "net discrepancy", which thus could be positive or negative.

Clearly the actual casting shrinkage of an alloy is a property of importance in any consideration of dimensional accuracy of castings, and various workers have made measurements which attempted to provide numerical values for the actual casting shrinkages of gold and various dental gold alloys. The methods they have employed can be broadly divided into two groups, direct and indirect (Hollenback and Skinner, 1946).

In all direct methods, specimens usually in the shape of rods or bars are cast into moulds whose length has been accurately measured. The difference between this length and the length of the resulting casting gives a measure of the casting shrinkage, usually expressed as a percentage of the original mould length. Direct methods have the advantage that the results are unequivocal, but the disadvantage that the casting shapes do not resemble those of usual dental castings.

Indirect methods involve measuring a wax pattern which may be of any shape, investing it in a suitable investment whose setting and thermal expansion have been determined under laboratory conditions, making a casting and measuring it. Summing any dimensional discrepancy between pattern and casting, and the total mould expansion theoretically provided by the investment, gives a measure of the actual casting shrinkage of the particular alloy used. Advantages of this approach are that castings can reproduce the shape of dental restorations, and practical laboratory techniques can be used. A severe disadvantage, however, is that it is impossible to be sure that the predicted setting and thermal expansions of the investment do occur in the casting ring.

#### 1.5.1 Direct Measurements of Casting Shrinkage

Price (1911) in his classical experiments using a vitreous silica mould reported linear casting shrinkage values for fine gold. It should be noted that he made direct measurements under conditions which did not reproduce those under which dental castings are made.

The values he reported were 1.64 per cent linear contraction occurring during the change of state from liquid to solid at a constant temperature of 1064°C for fine gold (the freezing point) and 2.20 per cent contraction of the solid gold on cooling from the freezing point to 0°C. However the value of 2.20 per cent is impossible as the thermal contraction of fine gold cooling through this temperature range cannot be greater than 1.78 per cent, based on its coefficient of linear thermal expansion over the range 20 - 900°C of  $1.67 \times 10^{-6}/K$  (Brandes, 1983).

Coleman (1926, 1928) investigated the casting shrinkage of fine gold and a number of gold alloys. In particular he determined a value for the actual casting shrinkage for coin gold (90 per cent gold, 10 per cent copper by mass). Coleman's specimens were cylindrical rods 3.25 in. long and 0.12 in. in diameter made in an investment mould. Under these conditions coin gold was found to have a linear casting shrinkage of 1.25 per cent.

Coleman reported that this value was not affected by the casting temperature of the alloy, nor by the mould temperature, at least within the range 40 - 300°C. This measured shrinkage was considerably less than the value for the true thermal contraction of the same alloy, determined experimentally. Coleman used a dilatometer to measure thermal contraction from 860°C (the highest temperature at which the specimen remained rigid) to 25°C. This curve, extrapolated to the solidus temperature of 926°C, gave a total linear thermal contraction after solidification of 1.62 per cent.

Coleman offered two possible explanations for the difference between the inherent casting shrinkage of 1.62 per cent and the actual shrinkage of 1.25 per cent observed in his experiments. These were that the shrinkage of the alloy may have been influenced by interlocking between the casting and the walls of the mould or that shrinkage on cooling of the partially solidified casting may be compensated for by the addition of molten alloy from the sprue, and that this compensation may be dependent upon a difference in the rates of cooling of different parts of the casting.

Hollenback and Skinner (1946) constructed an apparatus which they claimed made possible a more accurate determination of the casting shrinkage of gold and gold alloys by the direct method. They cast cylindrical specimens 1 in. in length and 0.22 in. in diameter and reported a casting shrinkage for fine gold of  $1.67 \pm 0.02$  per cent. For five different dental gold alloys the measured casting shrinkages ranged from  $1.37 \pm 0.00$  to  $1.54 \pm 0.01$  per cent.

The authors suggested that the variations in casting shrinkage from one alloy to another were probably caused by differences in composition, and speculated that Coleman's previously accepted lower value of 1.25 per cent casting shrinkage was the result of his unrealistically proportioned specimens (3.25 in. in length and 0.22 in. in diameter). However these two specimen sizes, though of different lengths, had substantially the same surface area to volume ratio, so the results obtained should have been comparable; the difference between their results could more reasonably be explained by the differences in composition of the alloys tested.

Earnshaw (1960b) cast rods 0.25 in. in diameter and 2.5 in. in length. Measurement of the actual casting shrinkage of fine gold gave an average value of  $1.74 \pm 0.03$  per cent which agreed well enough with the earlier results of Hollenback and Skinner. Earnshaw (1958), during his experiments on the casting shrinkage of cobalt-chromium alloys, found that increasing the diameter of the castings also increased the actual casting shrinkage. As Earnshaw's gold rods were slightly thicker (by 0.03 in.) than Hollenback and Skinner's this may explain the difference in the respective casting shrinkage values obtained for fine gold.

In 1980, Nakai, Nakamura, Seki et al., made measurements on specimens which were rectangular prisms 20 mm long and 3 mm by 5 mm in section. Their casting shrinkage figure for fine gold was  $1.73 \pm 0.04$  per cent which was almost identical to Earnshaw's results.

The linear coefficient of thermal expansion of gold is  $16.7 \times 10^{-6}/K$ . The calculated value for linear thermal contraction of fine gold, cooling from its freezing temperature of  $1064^{\circ}C$  to an average ambient temperature of  $20^{\circ}C$  is 1.74 per cent.

These results obtained by Earnshaw and by Nakai et al. suggest very strongly that in their experiments the full inherent casting shrinkage actually occurred in the specimens. On the other hand, Coleman in his earlier measurements on coin gold found that the actual casting shrinkage (1.25 per cent) was significantly lower than the calculated inherent casting shrinkage (1.62 per cent). In the light of the later measurements referred to above it is difficult to explain this discrepancy found by Coleman.

Finger and Jørgensen (1980) measured the thermal expansion of 12 gold alloys in a horizontal vitreous silica dilatometer. Specimens were heated to a temperature 50°C below the solidus temperature of the alloy and the total thermal expansion was determined by extrapolation. All the alloys exhibited total thermal expansions in the range 1.68 - 1.80 per cent. These were obviously experimental determinations of the inherent casting shrinkages of the alloys; Finger and Jørgensen assumed that they were also representative values for the actual casting shrinkage, and suggested that to produce an accurate casting the investment should be capable of a total mould expansion of at least 1.7 per cent.

#### 1.5.2 Indirect Measurements of Casting Shrinkage

Shell (1923) used an indirect method to measure casting shrinkage. He adapted wax to a rectangular steel mould 0.63 in. long. These patterns were invested and cast into hot moulds and room temperature moulds. Measurements for casting shrinkage were based on the discrepancy of fit of the castings when readapted to the original steel mould. Shell found that the casting shrinkage of gold in the high heat technique using a hot mould was 1.71 per cent and when castings were made into room temperature moulds a greater amount of 1.99 per cent was recorded. It is probable that this greater observed shrinkage was simply the result of casting into a mould which had not undergone thermal expansion.

Shell's results provide a good example of the problems involved in attempting to determine the casting shrinkage of alloys by indirect methods.

Scheu (1933) used measured wax patterns to cast small gold alloy blocks in investment moulds which had undergone known amounts of hygroscopic expansion, and which had a negligible thermal expansion, and then measured the castings. He found that an investment expansion of 1.5 to 1.6 per cent compensated for the casting shrinkage of a number of dental gold alloys. Castings in this study were also made from full crown patterns on a steel die, MOD patterns on a steel die and a 0.25 in. measured Class I or Class V type wax pattern. Scheu stated that when an investment with a 1.6 per cent expansion was used all these castings were dimensionally accurate. However, Scheu did not appear to make any measurements of the actual expansion of the investment moulds during setting, heating and casting.

Moore in 1952 reported the results of an investigation whose primary purpose was "to determine the amount of investment expansion required to entirely compensate for the casting shrinkage of a number of selected gold alloys". In effect, of course, he was making indirect measurements of their actual casting shrinkages.

He made castings to fit the National Bureau of Standards MOD steel die using investments whose total expansions had been determined by laboratory measurements during setting and heating. He found that an investment expansion of 1.75 per cent was required to compensate for the casting shrinkage of fine gold (a figure so close to the calculated value of 1.74 per cent that it appears to validate his experimental methods). He also found that the alloys he studied fell into two groups: one group made up of light-coloured soft gold alloys with apparent casting shrinkages of 1.67 to 1.75 per cent, and

a second group comprising dark-coloured soft gold alloys, medium hard and hard alloys, all of which showed apparent casting shrinkages of 1.55 to 1.67 per cent.

Fusayama (1959a, 1959b) made an extensive study of the casting shrinkage of gold and four dental casting alloys. He made what he stated were dimensionally stable wax patterns in the shape of Class I, MOD and full crown restorations. The measured wax patterns were cast in fine gold, three gold alloys and a base metal alloy, using a casting ring with a dry waterproofed asbestos liner, and an experimental investment with a measured setting expansion of 0.06 per cent, and a thermal expansion at 700°C of 1.34 per cent. This gave nominally a total mould expansion of 1.40 per cent. The castings were measured, and the amount by which they were undersize, added to the nominal mould expansion, was considered by Fusayama to give a value for the casting shrinkage of fine gold and the four alloys tested. In this way he obtained for fine gold an estimated casting shrinkage ranging from 1.97 to 2.11 per cent according to the shape of the casting. These values must be regarded with considerable reservation, as the unconfined thermal contraction of fine gold, from the freezing temperature to ambient, is only 1.74 per cent.

On the basis of his results, Fusayama claimed that the following values could be considered representative of the general casting shrinkages of gold alloys: (1) 2.1 per cent in simple inlays, (2) 2.0 per cent in crowns, and (3) 1.9 per cent in MOD inlays. Once again these figures are well in excess of the values for the total thermal contraction of solidified gold alloy castings determined by Finger and Jørgensen (1980) and this further

illustrates the difficulties encountered in making measurements of casting shrinkage by indirect methods.

### 1.5.3 The Effect of Alloy Composition on Casting Shrinkage

Some of the investigations already reported in Sections 1.5.1 and 1.5.2 included determinations of both inherent and actual casting shrinkage.

In the case of inherent casting shrinkage, Coleman (1928) determined the inherent casting shrinkage of fine gold and a series of binary gold alloys by extrapolating their thermal expansion curves to their solidus temperatures, both of which he determined experimentally. For fine gold he estimated an inherent shrinkage of 1.76 per cent, a value which agrees very closely with the figure of 1.74 per cent which can be calculated from more recently published data (Brandes, 1983). A series of experimental binary alloys showed significant variations in inherent casting shrinkage: gold with 10 per cent silver, 2.03 per cent; with 10 per cent copper, 1.62 per cent; with 10 per cent nickel, 1.91 per cent.

In an extensive study of casting shrinkages of fine gold and three inlay gold alloys of known compositions, Fusayama and Ogata (1966) made estimates of their inherent casting shrinkages by determining their thermal expansions from room temperature to their "softening points". Since their recorded softening point for fine gold was 1064°C, which is in fact its melting point, it seems likely that the softening points of the three alloys were very close to their solidus temperatures. It is difficult to accept the absolute values for thermal expansion given by these workers, as they report

an expansion of 1.99 per cent for fine gold, over the temperature range 20 to 1064°C, although this value can be calculated to be 1.74 per cent. However a reduction in measured thermal expansion was found as a result of alloying. Fusayama and Ogata claimed that the slopes of the thermal expansion curves as determined by them were similar for fine gold and the three alloys and so ascribed changes in inherent casting shrinkage to differences in solidus temperatures. The greatest reduction in thermal expansion was only 0.08 per cent (Type II alloy) so these differences in inherent casting shrinkage cannot be considered to be of practical importance.

Finger and Jørgensen (1980) made estimates in a similar way of the inherent casting shrinkage of 12 currently available dental golds representing Types II, III and IV alloys. Like Coleman, they heated the specimens to a temperature below their solidus temperatures (in their case 50K below) and obtained a value for the total thermal expansion by extrapolation. Although there were statistically significant differences in the estimated thermal contraction amongst the alloys tested, which could only have been the result of differing compositions, they found that these differences were relatively small, and unlikely to be of practical importance. The inherent casting shrinkages of all 12 alloys fell within the range 1.68 to 1.80 per cent.

In measurements of actual casting shrinkage, Hollenback and Skinner (1946) and Moore (1952) were also able to demonstrate variations which could be attributed to changes in alloy composition. Hollenback and Skinner, in direct measurements on fine gold and a series of commercially available dental gold alloys, found that all

the alloys had lower actual casting shrinkages than fine gold, ranging from 1.37 to 1.56 per cent, while fine gold had a shrinkage of 1.67 per cent. They also prepared a series of experimental alloys, by replacing some of the gold in a commercial 22 carat dark alloy with platinum or palladium, up to 15 atomic per cent in each case. In both cases the actual casting shrinkage was progressively reduced as the platinum or palladium content increased. Platinum had a more marked effect, the addition of 15 atomic per cent reducing the casting shrinkage from 1.50 per cent to 1.30 per cent.

Moore made indirect measurements of actual casting shrinkages of fine gold and a series of 61 commercial gold alloys and found that these fell into two groups. Fine gold and light-coloured soft (Type I) alloys required mould expansions in the range 1.67 to 1.75 per cent to produce dimensionally accurate castings, while for dark-coloured soft alloys and medium and hard alloys (Types II and III) expansions in the range 1.55 to 1.67 per cent were sufficient. One might suspect here that it was the addition of copper which reduced the casting shrinkages of the second group of alloys, and it will be remembered that in Coleman's (1926, 1928) measurements of inherent casting shrinkage copper was the most effective alloying element of the three studied, in reducing total thermal contraction of the alloy.

In the paper referred to earlier in this section (p.32), Fusayama and Ogata (1966) also reported on indirect measurements of the actual casting shrinkage of fine gold and three gold alloys. They claimed that to produce dimensionally accurate castings, the mould expansions required were 1.9 to 2.1 per cent for fine gold and

a Type I alloy, and 1.8 to 1.9 per cent for Types II and III alloys. Again these differences are not great enough to be of practical importance, and again the values obtained seem too high.

From the results of these various investigations, it can be concluded that although casting shrinkage does vary with alloy composition, the variation amongst gold alloys normally used for ordinary cast inlays, crowns and bridges is not large enough to warrant changes in investment expansion.

#### 1.5.4 The Effect of the Shape of the Casting on Casting Shrinkage

The direct measurements of observed casting shrinkage reported in Section 1.5.1 were made on specimens in the form of bars of varying shapes and sizes, but all of uniform cross-section. Thus interference with alloy contraction, by the investment mould, would have been minimal. However it has been recognised for many years that such interference could have a greater effect in castings of more complex shapes, especially if those shapes allow interlocking of the solidified alloy and the mould.

Following Coleman's (1926, 1928) measurements of the casting shrinkage of cast gold alloy rods, W.T. Sweeney, also working at the National Bureau of Standards, investigated the effect of varying the shape of the casting on the observed casting shrinkage. His data were unpublished but were later referred to by Souder and Paffenbarger (1942a) and Paffenbarger (1947). Sweeney's experimental methods were not considered as precise as those of Coleman. However he determined the casting shrinkage of gold alloys using pattern shapes which included spheres, spirals, and large and small rods,

some of which had anchoring wings at each end. The observed shrinkage ranged "from about 1 per cent to over 1.4 per cent, depending upon the amount of interlocking of the specimen in the investment" (Paffenbarger, 1947). Paffenbarger also commented: "It is definitely known that the size and shape of the casting affect the linear casting shrinkage".

As well as the measurements on cylindrical specimens already referred to in Section 1.5.1, Hollenback and Skinner (1946) made other tests using irregularly shaped patterns. Specimens with enlarged ends and with projecting spines, all showed a reduced casting shrinkage when compared with the original determinations on specimens of uniform cross-section cast from the same alloy.

An interrelated and equally important factor is the compressive strength of the investment. An investment with a high compressive strength at the casting temperature will be more effective than a weaker one in restricting casting shrinkage of a complex casting, and the effect will be greatest when interlocking of casting and mould is maximal (Earnshaw, 1958, 1969b).

When small dental castings (inlays and crowns) are considered it is obvious the effect of these two interrelated factors would be least in simple Class I and Class V castings, where interlocking between the alloy and the mould would be minimal. On the other hand in full crowns the effect would be greatest as the investment core opposes alloy contraction, especially in directions important to the fit of the casting. The effect of restraint imposed by the walls of the mould is even more complex in the case of the MOD inlay casting

as the restraint would vary in different important directions. It would be greatest in a mesio-distal direction where the investment core again opposes alloy contraction and least in bucco-lingual and occluso-gingival directions, where there is little interlocking of the casting and mould (Earnshaw 1969b).

In a series of investigations reported over a ten year period, Fusayama and various coworkers studied, amongst other factors, the effect of the shape of various practical dental castings on the actual casting shrinkage of gold alloys, using an indirect method developed by Fusayama (Fusayama, 1959a, 1959b, 1964; Fusayama and Ogata, 1966; Kono and Fusayama, 1969). A consistent finding was that the different types of restorations listed in the preceding paragraph did require differing amounts of mould expansion. Typical requirements were 2.1 per cent in simple inlays, 2.0 per cent for full crowns, 1.9 per cent for MOD inlays (Fusayama, 1959a, 1959b), 1.7 per cent for one piece bridge castings when vertically invested and 1.5 per cent when horizontally invested (Kono and Fusayama, 1969). Again it must be pointed out that, at least in the case of single inlay and crown castings, the absolute values for actual casting shrinkage seem to be impossibly high.

The effect of alloy shrinkage on the fit of MOD inlay castings is of particular interest. It has already been pointed out that restraint to shrinkage by the mould varies in different important directions. Alloy contraction could therefore be expected to be greatest in directions in which interlocking of casting and mould was minimal (i.e., in bucco-lingual and occluso-gingival directions) and this differential contraction could cause a distortion of the

casting. Therefore if an MOD inlay casting seats fully on its preparation, discrepancies could be expected in both occlusal and proximal sections.

In normal MOD cavity preparations these discrepancies would be masked by the marginal bevel; however in castings made to fit the National Bureau of Standards MOD die, which has no marginal bevel, these discrepancies could be expected to be visible, and in fact can be seen in illustrations published by Teteruck and Mumford (1966) and by Wald and Cocks (1971).

Because of considerations such as this, Earnshaw (1969b) recommended that the ideal investment should be no stronger after burn-out than necessary to resist forces set up during casting. This would then ensure that minimal distortion of the casting occurred while it was cooling after solidification.

All these observations support the contention that while for a given alloy the inherent casting shrinkage is determined only by its coefficient of thermal expansion and its solidus temperature, the actual or observed casting shrinkage will be lower by a varying amount, depending on the size and shape of the casting and the compressive strength of the investment mould at its burn-out temperature.

In conclusion, having recognised both wax pattern shrinkage and the marked casting shrinkage of inlay gold alloys, the problem then remains of selecting an investment expansion technique which will compensate for these dimensional changes.

## 1.6 GYPSUM-BONDED INVESTMENT EXPANSION

The knowledge that in the fabrication of cast gold restorations, the waxes and alloys used undergo a contraction has resulted in the development of investments which provide compensatory mould expansion. This compensation can be achieved by normal setting expansion, enhanced setting expansion in the presence of excess water (hygroscopic expansion) and thermal expansion or, more commonly, a combination of these (Phillips, 1982c; Craig, 1985a).

Dental casting investments are a mixture of a refractory (a heat resisting filler) and a binder, the refractory being similar in all types of investments while the binder varies according to the investment's application. Thus investments are classified into three groups depending on the type of binder present; these groups can be described as gypsum-bonded, silica-bonded and phosphate-bonded (Earnshaw, 1960a).

Gypsum-bonded investments are used for casting "low fusing" dental gold alloys, while silica-bonded and phosphate-bonded investments are used for casting alloys with higher liquidus temperatures ("high-fusing" gold alloys, palladium alloys and base metal alloys).

Gypsum-bonded investment powder has as its major ingredients a crystalline polymorph of silica (quartz or cristobalite, or occasionally a mixture of the two) present usually to the extent of 55 to 75 per cent, and calcium sulphate hemihydrate,  $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ , in the form of plaster or high-strength plaster (stone), as a binder.

There may also be small amounts (less than 5 per cent) of important modifying agents present (Souder and Paffenbarger 1942b; Earnshaw, 1978; Craig, 1985a).

Although the silica is referred to as the refractory component, in fact cast gypsum is sufficiently heat resisting to be used alone as a mould material, as it can be heated to temperatures as high as 1200°C without decomposing (Mori, 1985). In fact adding silica reduces its heat resistance, as in such mixtures, at temperatures above 900°C, the following reaction occurs (Earnshaw, 1960; Matsuya and Yamane, 1981):  $\text{CaSO}_4 + \text{SiO}_2 \rightarrow \text{CaSiO}_3 + \text{SO}_3$ . Crystalline silica is used in dental investments not to improve their heat resistance but to control dimensional changes on heating.

When cast gypsum is heated it shows a contraction which results from loss of water of crystallization, as the dihydrate reverts to calcium sulphate hemihydrate and then to  $\alpha$  calcium sulphate. A large contraction then accompanies the  $\alpha$  to  $\beta$  transformation in calcium sulphate, which occurs in the approximate range 300 - 400 °C (Earnshaw and Mori, 1985), and a further large contraction begins at about 600°C, which is probably the result of sintering (Earnshaw, 1975). The total linear contraction of cast gypsum prepared from dental plaster (W/P = 0.50) and heated to 700°C can be as high as 3 per cent (Earnshaw, 1978); the corresponding shrinkage for cast gypsum prepared from a high-strength plaster such as die stone (W/P = 0.25) would be about 1 per cent (Earnshaw, 1975). The latter is usually preferred as a binder for gypsum-bonded investments, not only because of its lower shrinkage on heating but because its superior strength when set allows a higher concentration of silica to be used

in the investment, so reducing still further the effect of binder contraction. As would be expected, additions of silica to the plaster binder cause a reduction in compressive strength which is linearly proportional to concentration (Earnshaw, 1978).

Silica,  $\text{SiO}_2$ , exists in 22 different condensed phases. Five of these are amorphous, and 17 crystalline (Sosman, 1965; Iler, 1979); the latter group are the polymorphs of silica. Of this group, only one phase, low ( $\alpha$ ) quartz is thermodynamically stable at normal temperature and pressure. Two more, tridymite S-I and low ( $\alpha$ ) cristobalite, exist under normal atmospheric conditions as metastable (but actually long-lived) phases.

Only two polymorphs of silica are of importance in dental investments, quartz and cristobalite, and both of them exist in a low temperature ( $\alpha$ ) phase and a high temperature ( $\beta$ ) phase. In each case the change between high and low temperature phases is rapid and readily reversible; it involves only a change in bond angles in the crystal structure (a displacive transformation) (Greener, Harcourt and Lautenschlager, 1972), so that only a small energy transfer is involved. This change is known as the low-high inversion.

Because in both quartz and cristobalite the high temperature phase is less dense than the low, the low-high inversion is accompanied by an isothermal expansion; this is added to the normal thermal expansion to give a large overall expansion at high temperatures.

As in all crystalline materials, single crystals of quartz and cristobalite show anisotropy of physical properties, including their coefficients of linear thermal expansion. However in dental investments they are used as a fine powder with random orientation of individual particles, so that in the aggregate they behave isotropically, and properties such as the coefficient of thermal expansion have a uniform average value.

Measurements of thermal expansion have been made on specimens of powdered quartz and powdered cristobalite, compacted into aggregates with a minimum amount of binder in the interstices. Under these conditions the thermal expansion of the specimens was essentially that of the silica component in dental investment.

Braesco (1920) obtained thermal expansion curves for cristobalite to 450°C, and quartz to 700°C. Earnshaw (1978) presented similar curves, but in both cases to 1000°C. His values for thermal expansion were higher than those published by Braesco, probably because care was taken in his experiments to minimize physical restraint to the specimen during heating. He found that the low-high inversion of quartz, which occurs at 573°C, gave an isothermal linear expansion of about 0.7 per cent, and the specimens had a total expansion at 700°C of 1.65 per cent.

In the case of cristobalite, the low-high inversion temperature ranges from 175 to 272°C according to the source of the sample and its previous thermal history (Sosman, 1965). Earnshaw (1978) has found that in the case of cristobalite used in dental investments the inversion occurs at about 250°C, and produces an isothermal expansion

of about 1.3 per cent. The cristobalite specimens showed a total expansion at 700°C of about 2.2 per cent. Dental investments designed to have a high thermal expansion usually contain cristobalite as the refractory.

During setting of the investment the silica is unaffected. The hemihydrate binder combines with water to form the dihydrate, gypsum, just as in the setting of other gypsum products (Earnshaw, 1978). The setting reaction is thus  $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O} + 1\frac{1}{2} \text{H}_2\text{O} \rightarrow \text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ . The set investment therefore consists of fine particles of silica, embedded in an interlocking aggregate of acicular gypsum crystals. The continuous porosity characteristic of cast gypsum provides venting of the mould cavity when a casting is made (Earnshaw, 1978).

Coleman (1926) observed that whenever any gypsum product set after mixing with water there was an observable setting expansion, presumably caused by growth pressure of the developing gypsum crystals. Adding silica to the hemihydrate powder increases its setting expansion, at least up to a silica content of 70 per cent (Earnshaw, 1978). Phillips (1982c) suggests that the silica particles inhibit the intermeshing of gypsum crystals during setting, so that more of the growth pressure is directed outwards.

It has been recognised for many years that gypsum products exposed to additional water during setting show an increased expansion. This phenomenon was studied extensively by Scheu (1932, 1933, 1935) who named it hygroscopic expansion. He developed and advocated a casting technique in which all the mould expansion was

obtained by immersing the filled casting ring in water while the investment was setting (Scheu, 1933).

The distinction often made between setting expansion and hygroscopic expansion (Craig, 1985a) is obviously a purely artificial one. The so-called hygroscopic expansion is simply an enhanced setting expansion which occurs in the presence of excess water. The generally accepted explanation, first advanced by Mahler and Ady (1960), is that in the presence of a continuous aqueous phase (and in the absence of external restraint) growth of gypsum crystals is unrestricted. If the continuous aqueous phase is maintained throughout the whole period of setting, by the supply of additional water from an external source, setting expansion reaches the maximum possible. This additional water can be provided by immersing the setting material in a water bath, by adding water to the free surface of the setting material, or by using a wet liner in a casting ring.

On the other hand, if additional water is not available, the volume of aqueous phase in the mix decreases as the setting reaction proceeds; at a relatively early stage in setting, shown by the disappearance of the glossy surface from the mix (Earnshaw and Marks, 1964) the continuous aqueous phase disappears, and free water in the mix is reduced to a film over the surface of the growing gypsum crystals. This occurs at the time that the mix loses fluidity and enters the plastic or mouldable stage of setting (Earnshaw and Marks, 1964), and shortly before the observed setting expansion begins (Earnshaw, 1964). Surface tension forces in this film of water exert a mechanical restraint on the growing crystals and reduce the overall expansion of the setting mass.

Modern methods for casting dental restorations can be classified as:

- 1) Thermal expansion techniques in which normal or hygroscopic setting expansion and thermal expansion of the investment mass both contribute importantly to mould expansion.
- 2) Hygroscopic expansion techniques in which all or most of the mould expansion is gained when the investment sets while exposed to additional water; here thermal expansion of the investment at the casting temperature is zero or very low (Earnshaw, 1978).

It is difficult to assign unequivocal values to setting and thermal expansion of an investment under practical conditions. Physical restraint applied to an expanding investment reduces its observed expansion. The wax pattern and casting ring will both offer some restraint to normal setting and hygroscopic setting expansion while the casting ring will inhibit some thermal expansion.

Laboratory measurements of setting and thermal expansion can be made under conditions of minimal restraint to obtain absolute values, but an unknown restraint is imposed on investment under practical conditions. In particular, the observed setting expansion of a given investment can vary greatly, even in different parts of the same investment mould. At best, any values given for mould expansion for a specific investment must be regarded as approximate (Earnshaw, 1964, 1966, 1967, 1969a).

#### 1.6.1 Setting Expansion Under Dry Conditions

During the setting of gypsum-bonded investments an expansion is observed which is greater than that of the hemihydrate binder alone.

Advantage is taken of this expansion to provide some of the mould expansion needed to compensate for alloy casting shrinkage.

The linear setting expansion of most inlay casting investments, measured under dry conditions while setting in air ranges from 0.1 per cent to 0.6 per cent (Earnshaw, 1978). The latest proposed revision (1985) of the American Dental Association Specification No.2 for casting investments (1962) states that for a Type 1 (inlay, thermal) investment the setting expansion in air at two hours should be between 0.0 per cent and 0.5 per cent. These figures are obtained by the traditional method, first described by Coleman (1926, 1928), of measuring the linear dimensional change which occurs as the investment sets in a V-shaped trough fitted with a dry non-absorbent liner. Expansion is measured by a non-contact method using comparator microscopes.

Therefore these measurements are made under dry and relatively unrestricted conditions and until the recent introduction of dry casting ring liners, the results thus obtained were not applicable to investments setting under practical conditions, when a wet liner is used in an alloy casting ring. In the casting ring the added water provided by the liner will increase the setting expansion by an unknown amount; conversely restrictive forces, to which the investment is very sensitive (Scheu, 1933; Skinner, 1933; Earnshaw, 1964), imposed by both the casting ring and complex wax patterns will reduce the setting expansion by an equally unknown amount.

Setting expansion is also affected by the W/P ratio, spatulation time and the rate of spatulation (Craig, 1985a). These

variables should be standardised to obtain reproducible setting expansion values.

When Coleman (1926, 1928) used the V-shaped trough to measure the setting expansion of investments, he lined the apparatus with waxed paper. A similar lining material was used by Taylor, Paffenbarger and Sweeney (1930) and Skinner (1933). Skinner also investigated the setting expansion of investments when confined by both soft and hard waxes. However, the heat liberated during setting softened the wax sufficiently to allow a setting expansion very similar to that recorded for unconfined specimens. Skinner then applied a load to the specimen during setting. The setting expansion was reduced to 30 per cent of its unconfined value by restrictive stresses of  $1500 \text{ g/cm}^2$  to  $2000 \text{ g/cm}^2$ . In these early experiments the frictional resistance of the waxed paper lining the trough was not recognised as a possible source of restraint upon setting expansion. Skinner concluded that the value for setting expansion when confined could be only roughly estimated and he was one of the first authors to advocate investments with a minimum setting expansion but with sufficient thermal expansion to provide the necessary mould expansion. This observation has since been supported by many others (Fusayama, Sukarai and Suzuki, 1957; Mumford and Phillips, 1958a; Fusayama, 1959a; van Aken, 1961; Earnshaw, 1969a; Finger and Jørgensen, 1980).

Watts (1946) and Docking and Chong (1949) measured the setting expansion of investments in casting rings. The rings were greased and unlined. Watts recorded the lateral expansion in the ring by the relative movement of two markers placed in the surface of the

investment. Docking and Chong set a needle on to a small acrylic base which was placed on the upper surface of the specimen. The vertical movement of the needle was measured with a cathetometer. To evaluate the restriction imposed by the metal casting ring these authors also used a split wax ring. Setting expansion in the wax rings was much greater than the minimal expansion observed in unlined casting rings, sometimes resulting in overcompensation.

Smyd (1948) used an unlined split metal ring and found that the lateral force of the setting expansion was great enough to open the ring. The filled split ring was invested in a second outer ring and setting expansion was still evident in both axial and lateral directions in the inner ring. This study showed the strength of the outwards force developed by the setting investment, which produces the observed setting expansion.

Jørgensen (1953) used a paper cylinder to measure the setting expansion of investment. Expansion in a vertical direction was measured with a dial gauge which exerted a force of 90 g and also with a Johansson Mikrokator which exerted a force during measurement of only 0.3 g. The latter instrument recorded the onset of the setting expansion in half the time compared with the dial gauge method.

Fusayama, Sakurai and Suzuki (1956, 1957) used a sectioned mould to make vertical specimens in the shape of square section prisms. The side walls of the mould were rapidly removed as soon as initial set occurred and a dial gauge was used to measure the vertical setting expansion of the free-standing specimen. This

method was also used by Fusayama, Hosoda and Kher (1961) who stated that the dial gauge exerted a spring force of 50 g.

Shell (1961) lined a rectangular trough with either tin foil or rubber dam to measure the effect of stresses of up to  $1000 \text{ g/cm}^2$  on the setting expansion of investment in a horizontal direction. Specimens set in the trough, one end of which was fixed and the other movable. Displacement of the movable end, caused by setting expansion, was measured by a counterbalanced dial gauge. Longitudinal force was applied to the setting investment by a loading system acting on the movable end of the trough. Vertical expansion was measured concurrently by following with a travelling microscope the movement of the upper end of a vertical piece of wire whose base was embedded in the centre of the specimen. In all cases the expansion in a vertical direction was much greater than that recorded by the dial gauge.

Earnshaw (1964) studied the behaviour of five different investments, some with a known high setting expansion and some with a low setting expansion. He recorded unrestricted setting expansion, restricted setting expansion under compressive stresses of up to  $800 \text{ g/cm}^2$ , setting expansion in a trough lined with rubber dam and finally setting expansion of specimens floating on mercury.

The unconfined specimens gave higher setting expansion results than when tested on the mercury bath. This was possibly because of the relatively high surface tension of mercury, which could exert some restraint on the setting expansion. The restraining effect of the trough and of applied restrictive forces was most marked in the

case of inlay casting investments. Clearly, before values for the setting expansion of investments have any absolute meaning, the restraint imposed by the measuring system must be known.

Jones and Wilson (1970) developed an extrusion method in which specimens were removed from a tapered mould for the measurement of unrestrained setting expansion. The transducer used to measure the expansion exerted a stress of only  $10^{-2}\text{N/cm}^2$  ( $1\text{ g/cm}^2$ ) on the specimen. The setting expansion values were generally far higher than those obtained by the split mould method of Earnshaw (1964, 1969a). This was attributed to the greater speed of mould removal in the extrusion method.

Finger (1980b) and Finger and Jørgensen (1980), used the dial gauge method but cast specimens of experimental investment into paper cylinders to measure setting expansion. In this study the measuring load exerted by the dial gauge was reduced to  $25\text{ g/cm}^2$ . Finger (1980a) also compared this method with the test procedure given in the American Dental Association Specification No.25 for dental gypsum products (1973) and found that the dial gauge method gave higher setting expansion values.

Many methods have been developed to measure the setting expansion of investments. In most cases some restraint is exerted on the setting expansion by the method of measurement. The restrictive forces exerted on the setting expansion of investments under practical conditions are unknown as is the resulting reduction in the expansion of the investment.

### 1.6.2 Setting Expansion in the Presence of Additional Water

Since the discovery by Scheu (1932) that the setting expansion of investment is greatly enhanced in the presence of excess water, many studies have been made of the so-called hygroscopic setting expansion effect. Contact with water may be achieved by immersing the filled casting ring in a water bath, by the addition of a known quantity of water to the exposed surface of unset investment in the casting ring, or by lining the casting ring with wet asbestos prior to investing the wax pattern (Scheu, 1932, 1933, 1935; Hollenback, 1948; Asgars, Mahler and Peyton, 1955; Earnshaw, 1969a, 1978).

The magnitude of hygroscopic setting expansion is directly related to the quantity of water added during the setting period until a maximum expansion has occurred; no more expansion is then evident regardless of any further water addition (Asgarzadeh, Mahler and Peyton, 1954; Mahler and Ady, 1960).

The amount of hygroscopic setting expansion is also directly related to the refractory content in the investment powder. Investments designed for use in thermal expansion techniques, which have a high silica content, can have a setting expansion under water, measured with minimal constraint, as high as 4 per cent (Earnshaw, 1978). However even small restraining forces cause a large reduction in hygroscopic setting expansion and when measured under usual laboratory conditions the hygroscopic setting expansion of most investments is in the range of 0.3 per cent to 2.0 per cent (Earnshaw, 1978). The American Dental Association Specification No.2 for casting investment (1962) requires that the expansion of a Type

II (inlay, hygroscopic) investment, setting while immersed in water, should be between 1.2 per cent and 2.2 per cent.

Like setting expansion under dry conditions, setting expansion in water is sensitive to the effect of manipulative variables. These variables include the presence of restraining forces, the W/P ratio, the rate and time of spatulation, the age of the investment; and more specifically, the time of immersion and the availability of excess water (Scheu, 1932, 1933, 1935; Docking, Donnison and Chong, 1948; Landgren and Peyton, 1950; Delgado and Peyton, 1953; Asgars, Mahler and Peyton, 1955; Peyton, Mahler and Asgar, 1956; Earnshaw, 1969a; Jones and Wilson, 1970).

In hygroscopic expansion techniques the mould is heated to about 500°C, at which temperature the thermal expansion is relatively low as the quartz filler does not undergo inversion until heated to 573°C (Earnshaw, 1978).

The water-bath immersion technique was developed by Scheu (1932, 1933). The investment filled ring was submerged in a water bath held at 38°C while the investment set. The investment used was capable of very little thermal expansion at the recommended casting temperature which was less than 320°C. The reason for using warm water was to soften the wax pattern, which would then offer less restraint to the expanding investment.

In 1935, Scheu recognised that enhanced setting expansion also resulted when investment set in contact with both wet and dry asbestos ribbon, and suggested lining casting rings with wet asbestos

as an alternative hygroscopic expansion technique. When Souder (Hollenback, 1962) introduced the wet asbestos casting ring liner its purpose was to provide a cushion for thermal expansion of the investment. Although its ability to enhance setting expansion, by a normally unrecognised amount, was clearly demonstrated by Scheu, the wet asbestos liner has traditionally been used in investment thermal expansion techniques and not as a recognised hygroscopic setting expansion method.

Hollenback (1943, 1948) combined Scheu's methods when he lined casting rings with wet asbestos and suggested the immediate immersion of the filled ring in a warm water bath. Earlier immersion of the casting ring combined with the use of an investment heated to a casting temperature of 480°C contributed to a large overall expansion of the investment mould.

The development of casting techniques based on hygroscopic setting expansion, by both Scheu and Hollenback, exemplified an empirical approach, and they did not attempt to advance any explanation for this phenomenon.

In the nineteen forties and fifties some important investigations were described which sought an explanation for the mechanism responsible for this greatly increased setting expansion under wet conditions. Degni (1946), whose results were not published until later (Skinner and Degni, 1957), measured setting expansion in the traditional V-trough lined with waxed paper, on specimens immersed in water at 37°C. He found that the waxed paper produced sufficient frictional restraint to reduce the observed expansion.

When the trough was lined with foil, mineral oil and wet asbestos the asbestos gave the greatest expansion because of the added water present rather than as a result of decreased constraint. The sensitivity of setting expansion to physical restraint was also evident when the dial gauge method of measurement was used with submerged casting rings. When the measuring system was counter-balanced the recorded expansion was doubled.

Docking and co-workers (Docking, Chong and Donnison, 1948; Docking, Donnison and Chong, 1948) measured the hygroscopic setting expansion of relatively unrestrained investment specimens. The unset mix was poured on to a mercury bath and immersed in warm (30°C) water. Length changes were measured by a non-contact method, using a travelling microscope, and the effect was studied of several important factors. Cooling of the water bath did not significantly decrease the observed setting expansion; and a fine silica particle size, a high silica content, a decreased W/P ratio and a minimum time interval between mixing and immersion of the specimen all increased the observed expansion.

Similar results were obtained when the hygroscopic setting expansion of investment was measured in casting rings immersed in a water bath (Docking and Chong, 1949; Landgren and Peyton, 1950). The vertical movement of a needle supported on the surface of the setting investment was measured with a cathetometer. The greatest expansion was obtained when the investment was immersed before initial set. Also investments designed for hygroscopic expansion gave more uniform results than those intended for thermal expansion techniques.

The sensitivity of hygroscopic setting expansion to restrictive forces was reported by Delgado and Peyton (1953). They stated that the dial gauge method commonly used to measure setting expansion under dry conditions was not sensitive enough to distinguish between moderate differences in expansion under hygroscopic conditions. However the non-contact measuring method first used by Docking et al. (1948) yielded higher and more reproducible values. Also the addition of borax which powerfully reduces setting expansion under dry ambient conditions had the same effect on setting expansion under water, decreasing the expansion appreciably depending on the concentration.

Asgarzadeh, Mahler and Peyton (1954) and Asgars, Mahler and Peyton (1955) used both solid and four part sectional inlay rings to measure the axial and lateral expansion of investment when immersed, in contact with wet asbestos and after the addition of known quantities of excess water. These studies showed an almost linear relationship between the amount of expansion and the quantity of added water. Based on this observation they developed a hygroscopic expansion technique which relied on the addition of controlled amounts of water to achieve the desired setting expansion. The lateral expansion studies had demonstrated the restrictive effect of the metal casting ring, and the wet asbestos liner gave erratic hygroscopic expansion results. Therefore in this method, a flexible unlined rubber inlay ring was used with a brass reservoir designed to fit the ring which received the added water. As the rubber ring was removed before burn-out and casting, an investment with a high strength was recommended. This water-added hygroscopic expansion technique gave results of good reproducibility and is the second of the two recognised hygroscopic expansion techniques.

In an attempt to explain the mechanism of hygroscopic setting expansion, Lyon, Dickson and Schoonover (1955) replaced the silica component in an experimental investment by mixing powders such as pumice, graphite, talc and silica with Hydrocal, a high-strength gypsum plaster. When these fillers were added to Hydrocal there was a marked increase in hygroscopic setting expansion.

Ryge and Fairhurst (1956) replaced some of the water in the mix with other liquids such as ethyl alcohol, glycerine and a number of oils. In all cases some hygroscopic expansion was observed.

Results similar to those obtained earlier by Degni (1946) were reported by Shell (1961). He found that a stress as small as  $10 \text{ g/cm}^2$  was sufficient to reduce hygroscopic setting expansion.

Mahler and Ady (1960) substantiated their explanation for the mechanism of hygroscopic setting expansion by reducing the surface tension of the added liquid with surfactants. These resulted in a definite increase in the linear expansion of the investment. Mercury, oils, glycerine and ethylene glycol also gave different expansion results, the least being observed with mercury and liquids which were immiscible with water. These authors were able to demonstrate a direct relationship between the presence and quantity of added water and the onset and extent of enhanced setting expansion.

Earnshaw (1969a) repeated his earlier study of the effect of physical restraint on setting expansion in air (1964), on specimens immersed in a water bath during setting, to determine the effect of

restraint on hygroscopic setting expansion. Inlay investments designed for thermal expansion techniques in particular were capable of large setting expansions in water when unconfined, but these large expansions (as high as 4 per cent) were very sensitive to even small restrictive forces. Similar results were obtained by Jones and Wilson (1970).

Casting techniques in which the casting ring is lined with wet asbestos cause a similar increased setting expansion of the investment, and this effect is most marked when a high silica content (thermal expansion) investment is used. The presence of restrictive forces imposed by both complex wax patterns and metal casting rings complicate the conditions still further. Although this traditional technique has been used successfully for many years, the suggestion is understandable that investments with a minimum setting expansion should be used with a waterproofed liner to provide a cushion for the thermal expansion of the investment (Skinner, 1933; Fusayama, Sakurai and Suzuki, 1957; Mumford and Phillips, 1958a; Fusayama, 1959a; Shell, 1969).

### 1.6.3 The Effect of Setting Expansion Under Practical Conditions

In both the hygroscopic and thermal expansion techniques a substantial setting expansion of the investment can result from the presence of excess water from any external source or from the wetted casting ring liner. Under practical conditions the setting expansion of the investment will be restrained by both the casting ring and complex wax patterns. Conversely wax patterns may become distorted by the expanding investment especially if they are thin or fabricated from soft wax. Elevated temperatures from either the exothermic

setting reaction of the investment or the warm water bath immersion technique may also result in softening of the pattern and subsequent distortion. These factors have been extensively studied to determine the nature of the effective setting expansion of investments under practical conditions.

Van Horn (1910, 1920) suggested that wax patterns formed in the mouth should be maintained at 38°C until the investment had set. This method was known as the expanded pattern technique. However, after observing the distortion of MOD wax patterns when floated on water baths at elevated temperatures, Maves (1932) concluded that this technique would result in non-uniform expansion of the wax with considerable accompanying distortion.

Skinner (1933) recorded the heat evolved by two investments when setting which was 9.9°C and 6.3°C respectively. He concluded that wax expansion which occurred while the investment was setting was not caused by force exerted by the expanding investment but was the result of the heat liberated during setting.

Smyd (1948) concluded that the force of expanding investment which he had observed in a split inlay ring was large enough to deform complex wax patterns. He suggested that soft waxes should be used to form patterns as these would offer less resistance to the expanding investment and ensure more uniform mould expansion. Crown patterns formed from a soft wax, invested and immersed in a water bath held at 43°C, gave more accurate castings than those made from a regular inlay wax under the same investing conditions. This method

was also recommended for wax patterns made on stone dies by the indirect technique (Smyd, 1953).

To determine the effect of the setting expansion of investment on MOD wax patterns, Jørgensen (1953) measured the distance between a number of metal pins embedded in the patterns. The patterns were invested in paper cylinders with both quartz and cristobalite investments. In some cases the invested patterns were immersed in water baths after various time intervals and at various temperatures. The invested patterns were sectioned after 24 h to expose the pins and the measurements were repeated. Jørgensen found that the setting expansion under dry conditions was restricted by the proximal boxes of the wax patterns. Thinner patterns allowed greater expansion than thick patterns with some separation at the cervical ends of the boxes. The force of the expansion with the immersion technique was so great that patterns made from a hard wax with a thin occlusal portion broke at the junction of the proximal and occlusal wax.

Suffert and Mahler (1955) measured full crown wax patterns which had been annealed for 24 h at ambient temperature. Castings made by thermal and hygroscopic techniques were also measured to determine the reproducibility of a number of investing techniques. The wax patterns appeared to prevent the expansion of the core of investment at the pulpal floor level more so than at the shoulder of the pattern; and this effect was more pronounced with hygroscopic setting expansion techniques. The authors suggested using a warmer water bath held at 51°C and a softer wax to allow more uniform hygroscopic setting expansion. This method was originally recommended by Smyd (1948).

Full crown and MOD castings made by Fusayama, Sakurai, and Suzuki (1957), with the thermal expansion technique, were significantly distorted when the casting ring was lined with wet asbestos. Dry asbestos resulted in less distortion with a more uniform expansion of the mould and unlined casting rings produced very undersized castings exhibiting the least distortion. They suggested waterproofing the casting ring liner to eliminate the undesirable hygroscopic expansion effect evident when both wet and dry asbestos were used. The mean temperature rise during setting of the investment was  $2.5^{\circ}\text{C}$  which they stated would result in a thermal expansion of the wax pattern of 0.05 per cent. To eliminate wax pattern distortion these authors recommended that the setting expansion of investments should be decreased to 0.05 per cent to harmonize with the predicted thermal expansion of wax patterns. Naturally such an investment would need a very large thermal expansion to provide the necessary compensation for the casting shrinkage of gold alloys.

Fusayama (1959a, 1959b) partially embedded MOD wax patterns made from regular inlay wax and soft paraffin wax. The exposed surface of the wax was photographed after two time intervals and the outline of the patterns was traced from the negatives to determine the extent of pattern distortion. The most severe distortion was found with the water bath immersion technique where there was bending of the occlusal portion and an opening between the floors of the boxes. The least distortion in this study was found when an experimental investment with a setting expansion of 0.02 per cent was used. Castings from MOD and square plate patterns were made to compare the distortion seen with unlined steel casting rings, rubber

casting rings and the added water technique, wet asbestos and waterproofed asbestos. Again the most severe distortion of the MOD castings was observed with the hygroscopic technique and the square plate castings were generally undersize and indicated a lack of reproducibility with this technique. Erratic results were also obtained with the wet asbestos casting ring liner and all castings made in unlined rings were undersize. When the liner was waterproofed and used with an experimental investment with a setting expansion of between 0.04 per cent and 0.07 per cent the distortion was eliminated.

The degree of distortion of wax patterns by gypsum-bonded investment setting expansion under both dry and hygroscopic conditions was investigated by Mumford and Phillips (1958a). A stainless steel MOD die heavily engraved with reference lines at the axio-pulpal line angles and the gingival floors was used to make patterns which were vacuum invested. After setting for 24 h the moulds were sectioned and the wax eliminated to reveal the reference marks which were measured. The difference between these readings and the measurements of the die represented the change in dimension of the wax pattern during setting expansion of the investment. Four investing techniques were used and patterns were invested in six different positions in the ring. Severe distortion was indicated by a convexity at the occlusal of the mould space accompanied in some cases by a contraction across this area. This was possibly because of the force of the investment at the gingival of the pattern which caused the proximal boxes to act as lever arms, resulting in a compression of the investment at the occlusal. Both expansion and distortion of wax patterns were greater when the patterns were

positioned near the closed end of the ring and when placed closer to the side of the casting ring. The movement of pins, attached to the sides of the patterns and protruding through holes in the casting ring, indicated that distortion of the patterns started one minute after initial set of the investment and ceased within one hour from the beginning of mixing. These workers also identified an area of contraction at the centre of the ring which indicated that investments undergo unequal expansion throughout their mass when confined in casting rings. This factor represents a constant source of possible distortion of wax patterns.

Van Aken (1961) embedded small lead markers on the proximal surfaces of MOD wax patterns. A casting ring with acrylic windows was used so that the position of the lead pieces could be periodically radiographed to assess the distortion of wax patterns of different thicknesses invested by several thermal and hygroscopic investment expansion techniques. Thin wax patterns and hygroscopic expansion techniques which included a warm water bath produced the greatest distortion and the most expansion.

Mahler and Ady (1963) used a method similar to Mumford and Phillips (1958a) but made Class V and full crown wax patterns as well as MOD patterns with both regular inlay wax and soft wax. Patterns were annealed at room temperature for 72 h before being invested in both thermal expansion and hygroscopic expansion investments in different positions in the asbestos lined casting rings. There was a significantly increased effective setting expansion when the patterns were invested near the centre of the ring. Distortion of the gingival parts of the MOD patterns was characteristic and was greater

than that seen with the full crown patterns, demonstrating the restriction to setting expansion of the core investment by the walls of the full crowns. One of the conclusions made from this study was that the effective setting expansion in the casting ring was very different from the value obtained from linear trough expansion measurements. The vertical position of the wax pattern in the casting ring was considered to be one of the most significant factors which influenced effective setting expansion.

Soft, medium and hard waxes were used in a subsequent study (Mahler and Ady, 1965) to make MOD patterns which were invested and immersed in water baths at 21°C and 38°C with and without contact with the water in the bath. There was a marked increase in the expansion of the wax pattern when the water bath temperature was increased. This expansion of the wax was attributed not to the hygroscopic setting expansion of the investment at an elevated temperature but to softening and expansion of the wax. This suggests that the hygroscopic expansion technique introduced by Scheu (1932) could be described as a wax expansion technique, a method first described by Van Horn in 1910. There was also a general tendency for an increase in the effective setting expansion when soft wax was used to form the patterns but this expansion was not uniform and under hygroscopic setting conditions sometimes resulted in an inward distortion of the pattern. The results indicate that the strength properties of waxes are of importance since these are subjected to the forces exerted by the expanding investment and to temperature changes during setting of the investment.

In 1967 Mahler continued his study on the effect of hygroscopic setting expansion and the role of elevated temperatures. He again concluded that temperature played a greater role than did the hygroscopic expansion effect in the fit of full crown castings measured on a steel die. Mahler suggested altering the water bath temperature as a means of adjusting the necessary compensation rather than relying on effective hygroscopic setting expansion alone.

Shaheen (1967) used a very different method to observe the behaviour of investments around wax patterns. A capillary tube connected to a cavity within a modified wax pattern recorded the change in volume of water in the cavity which in turn indicated the expansion of the investment. The outer surfaces of the proximal boxes of the MOD patterns and the inner surface of the occlusal portion were subjected to tensile stresses while the occlusal of the pattern and the inner surfaces of the boxes were subjected to compressive stresses.

Ohno, Miyakawa and Shiokawa (1982a, 1982b) used an epoxy resin MOD pattern in a two part split casting ring with a number of investing conditions including the use of dry asbestos waterproofed with both silicone grease and vaseline.

The pattern was exposed after the investment had begun to set and isochromatic lines in the resin were photographed periodically. The distortion of the resin pattern commenced coincidentally with the setting expansion and the rate of deformation coincided with the rate of investment expansion. Again displacement of the proximal boxes occurred, and this resulted in bending of the occlusal portion.

To overcome this distortion of MOD wax patterns by expansion of the setting investment a technique has been developed which uses waxes with different elastic moduli for the occlusal and proximal portions of the pattern (the dual-wax technique) (Charbeneau and Peyton, 1958; Craig, Eick and Peyton, 1967; Cecconi and Asgar, 1975).

However the use of investments with a substantial thermal expansion and an extremely low setting expansion is probably the most popular and acceptable means by which the problems of distortion of wax patterns by the setting expansion of investment and restriction of the setting expansion by complex wax patterns may be overcome (Skinner, 1933; Fusayama, Sakurai and Suzuki, 1957; Mumford and Phillips, 1958a; Finger, 1980b).

#### 1.6.4 Thermal Expansion of Investments

The investment used by Taggart (1907) contained 57.5 per cent quartz and, when heated to a cherry red colour (about 700°C), had a thermal expansion of 0.77 per cent (Shell, 1960; Hollenback, 1962). Lane (1909b) and Van Horn (1910) used investments with a higher refractory content to increase the thermal expansion of the investment. These early investments contained low strength gypsum plaster as the binder, and this gives a set mass which undergoes a considerable shrinkage when heated (Earnshaw, 1978). The addition of boric acid (Weinstein, 1929) and sodium chloride (Moore, 1933) reduced the shrinkage of the binder, and this resulted in an increased thermal expansion of the investment (Shell, 1960).

Taylor, Paffenbarger and Sweeney (1930) developed an investment which contained 75 per cent cristobalite and which had a thermal expansion of 1.27 per cent at 700°C when mixed in a W/P ratio of 0.42. It was at this time that the asbestos liner was introduced to provide a cushion which allowed expansion of the investment in a lateral direction in the casting ring (Hollenback, 1962). The traditional dry calcined plaster binder was replaced by a high strength autoclaved plaster marketed under the trade name Hydrocal. Its higher strength allowed the development of investments with a decreased binder content and therefore a higher percentage of refractory (Shell, 1960).

The American Dental Association Specification No.2 for casting investments (1962) stipulates that a Type I (thermal) investment should expand between 1 per cent and 2 per cent at 700°C; and the combined setting and thermal expansion should fall between 1.3 per cent and 2.0 per cent.

Earnshaw (1961) increased the thermal expansion of a commercial dental investment from 1.1 per cent to 1.5 per cent at 700°C by mixing it with a 10 per cent glycerol solution instead of water. He subsequently (Earnshaw, 1975) developed experimental investments in which a combination of 0.2 per cent sodium chloride in the powder and 10 per cent glycerol in the mixing solution produced thermal expansions as high as 1.7 per cent at 700°C.

The thermal expansion of investments is also sensitive to changes in W/P ratio, decreasing with thinner mixes (higher W/P ratios) (Volland and Paffenbarger, 1932; Mahler and Ady, 1963;

Shell, 1968; Earnshaw, 1978). Therefore the presence of excess water, either from a wet liner or in a hygroscopic expansion technique, also reduces thermal expansion, as the addition of this water to the investment during setting has exactly the same effect as if it were added during mixing (Macasaet and Dickson, 1962; Earnshaw, 1967).

Earnshaw (1966) investigated the effect of restrictive stresses of up to  $1000 \text{ g/cm}^2$  on investments designed for thermal expansion techniques. As these investments have a relatively low compressive strength, the effect of restrictive forces from laboratory measuring systems and under practical conditions in casting rings is important. Jones and Wilson (1968) applied stresses which ranged from  $1.8 \text{ g/cm}^2$  to  $1,300 \text{ g/cm}^2$  to investments heated to  $700^\circ\text{C}$ . This study again illustrated the sensitivity of thermal expansion to even small constraining forces.

Mumford and Phillips (1958b) determined the thermal expansion of investment in the casting ring by recording the movement of the walls of an MOD mould when heated to the burn-out temperature. Two layers of wet asbestos resulted in a greater expansion of the gingival floors of the boxes; not however because of an increased thermal expansion but as a result of the improved cushion and more importantly the enhanced setting expansion provided by the added water in the liner. When the patterns were invested near the closed (crucible former) end of the ring the increased expansion of the mould was considered to be a result of increased thermal expansion as the investment mix was thicker in this part of the casting ring. The expansion of the investment was reduced to only 0.5 per cent in areas

of the investment mass near the casting ring when it was lined with a single layer of asbestos. However a much greater expansion was evident, under the same conditions, in those parts of the mould which were not connected to the walls of the casting ring by a continuous mass of investment. This applies particularly to the part of the investment core which represents the pulpal floor of the occlusal section of the MOD cavity. These findings support the recommendations made by others that a thick and waterproofed dry liner would eliminate both restrictive forces imposed by the casting ring and the erratic hygroscopic expansion effect seen with wet liners (Fusayama, 1959a; Hanari, 1967).

Hollenback and Rhoads (1960b, 1960c) also recorded a marked reduction in the thermal expansion of investment in casting rings lined with both wet and dry asbestos, compared with the expansion of free standing specimens. Measurement of the mould space which developed around an invested vitreous silica cylinder gave the same results. The conventional method of lining a casting ring to within 3 mm of either end of the ring in accordance with the American Dental Association Specification No.2 for casting investments (1962) also resulted in a decreased overall expansion of 1.0 per cent. However when a full length liner was used the expansion was 1.4 per cent which was considered as an acceptable enlargement of the mould to compensate for gold alloy shrinkage.

Shell and Hollenback (1965a) were also unable to obtain adequate mould expansion when short liners were used. They invested measured wax cylinders which were cast at three mould temperatures. The short liner in the ring resulted in castings 0.61 per cent

smaller than the patterns when cast at 650°C, and the total expansion of the investment was 1.07 per cent. Full length liners allowed a final expansion of 2.09 per cent at the same temperature. Shell (1969) used the invested vitreous silica cylinder method and obtained a total expansion of 1.35 per cent with a waterproofed full length liner. This value reflected the reduction in the setting expansion of the investment when in contact with a dry, and more importantly, non-absorbent liner and emphasised the need for an investment with a greater thermal expansion when coupled with the use of a waterproofed liner (Fusayama, 1959a).

In several studies, the thermal expansion of investments was evaluated by assessing the fit of full crown, MOD and three-quarter veneer castings (Teteruck and Mumford, 1966; Jenkins and Phillips, 1971). They found that the expansion of the investment in the casting ring was less than that stated by the manufacturers and resulted in undersized castings; the difference was particularly evident with extracoronary restorations.

In conclusion it must be emphasized that an unknown restraint imposed by the casting ring coupled with an unknown amount of water absorption and hygroscopic expansion when wet liners are used can result in a variable and erratic expansion during both setting and heating of the investment. Many authors have shown that this factor can result in undersized and distorted castings, and this has undoubtedly resulted in the recommendation that a desirable investment for the thermal expansion technique should be strong enough to be used without a casting ring and liner, with a minimum setting expansion and a maximum thermal expansion of approximately

1.7 per cent (Skinner, 1933; Fusayama, 1957; Hanari, 1967; Finger, 1980b).

#### 1.7 THE CASTING RING AND ITS LINER

When Taggart (1907) introduced his casting technique to dentistry he did not describe the casting ring, or "flask" as it was then known in any way. However Lane (1909a) did mention that brass was the metal used to make casting rings and Van Horn (1911) described the "flask" as having been cast from bronze or high grade brass.

The need for a casting ring liner was first suggested by Wilmer Souder (Hollenback and Rhoads, 1960b; Hollenback, 1962, 1964). Although cristobalite had been introduced as the refractory in investments, its potentially high thermal expansion was not achieved in an unlined casting ring. Early results with this new material were disappointing as most of the castings were undersize. Souder recognized that this discrepancy occurred because the thermal expansion of the investment was greater than that of the metallic casting ring. This naturally would cause a decrease in effective thermal expansion of the investment in the ring. In fact, investment expansion directed inwardly by the rigid casting ring would cause a reduction in the volume of the mould cavity. Souder suggested that a soft liner which would act as a cushion should be placed in the ring as this would permit the investment to undergo its full thermal expansion.

Taylor, Paffenbarger and Sweeney (1930) were the first to describe the technique of lining brass casting rings when these were

to be used with cristobalite investments. They stated that a layer of wet asbestos paper should be pressed firmly against the inside of the casting ring and that both ends of the asbestos should be trimmed to be short of the edge of the ring; at one end to allow adaptation of the crucible former to the ring and at the other to leave approximately 6 mm of exposed casting ring.

The American Dental Association Specification No.2 (1962) for dental investments, which was originally published in 1930, as a result of the work of Taylor et al., includes an illustration of a casting ring which clearly shows that the liner should be 3 mm short of each end of the casting ring and that the specified thickness of the liner was 0.8 mm when wetted.

In 1934 Van Horn noted that the conventional inlay flask was a brass tube with a solid wall. He questioned the validity of comparing laboratory measurements of the setting and thermal expansion of investments with the investment expansion when confined by a casting ring. Since the brass casting ring had a lower thermal expansion than the investment he suggested that the added investment expansion was either not obtained or only occurred in an axial direction. This led him to question the effect of these differing expansions of the casting ring and the investment on the dimensions of the mould within the investment at the casting temperature. Van Horn showed graphically that whereas a cristobalite investment expanded 1.35 per cent at 600°C, a brass casting ring expanded 1.3 per cent, a Monel metal casting ring 0.9 per cent and a stainless steel casting ring 0.7 per cent at the same temperature. He believed that this difference in expansion resulted in warpage of the mould

which could be prevented by fitting the ring with a loose asbestos liner.

Rice (1931) expressed concern at the confining effect of unlined brass casting rings on the setting expansion of investment materials. In order to determine whether the setting expansion was totally prevented or directed centrally towards the wax pattern he invested a tapered brass plug in an unlined brass casting ring. This was removed at the time of initial set of the investment and after the final set of the investment the plug was resealed. It was found that the hole had decreased in size as the brass plug could not be fully relocated. The experiment was repeated with a split casting ring capable of lateral expansion and in this case the plug fitted very loosely. Rice therefore established that the setting expansion of the investment would be in an inward direction if there were restraint imposed by an unlined rigid casting ring.

Ray (1933) studied the behaviour of various metals used in casting rings. He stated that the commonly used brass casting rings were unsatisfactory as they oxidized and scaled at high temperatures; also as a result of annealing they became soft and easily deformed after several uses. Ray surveyed a number of other metals and alloys with the hope of finding a more satisfactory material. He considered that the metal used in the construction of an inlay ring should ideally be non-corrodible, hard and strong with a thermal expansion similar to that of the investment used. Ray noted that the asbestos liner placed inside the ring would compensate for any minor differences in the thermal expansions of the investment and casting ring. Tests he made indicated that a ring of asbestos paper could

easily be compressed 0.5 mm which would allow the diameter of the investment to increase the same amount. Ray stated that this would be equal to an expansion of the investment of about 1.3 per cent, an amount great enough to allow for any setting expansion as well as the difference in the thermal expansion of the inlay ring and the investment.

The composition and properties of six metals and alloys were tested. These included iron, copper, brass, nickel, Monel metal and stainless steel. The thermal expansion of these materials at 700°C ranged from 0.95 per cent for iron to 1.40 per cent for brass. Ray concluded that inlay rings made from iron, copper and brass were the least acceptable as iron tended to rust, while copper and brass scaled when heated, were too soft and were easily deformed. Nickel was considered more satisfactory as it did not corrode or scale but still could be easily deformed. Monel metal rings tended to corrode but were otherwise considered to be suitable. His final recommendation was that stainless steel, although relatively expensive, produced the hardest, strongest and most acceptable inlay rings. The thermal expansion of this metal was 1.20 per cent at 700°C which Ray considered was compatible with the expansion of investments provided an asbestos liner was used.

In 1933 Skinner discussed the importance of investment setting expansion and like Rice recognized that the asbestos liner also served as a cushion to permit this expansion to occur.

However, a well documented side effect which accompanied the use of a wet asbestos liner was the increased setting expansion of

the investment. This effect was first reported by Scheu (1935), who observed it when either wet or dry asbestos was used as the liner. It has been shown that this hygroscopic expansion effect is both erratic and of an unknown amount. It is caused by absorption of water from the liner into the investment mix. In order to eliminate this expansion some authors have advocated waterproofing the asbestos liner with cocoa-butter or petroleum jelly (Fusayama, 1959a; van Aken, 1961; Shell, 1969).

Brumfield, quoted by Docking and Chong (1949), showed from both mathematical calculations and mechanical testing that the maximum lateral setting expansion of an investment which could be expected in an unlined metal casting ring was of the order of only 0.03 per cent.

A number of authors have compared the effect of a lined casting ring with an unlined ring on the expansion of the investment during setting and subsequent heating.

Fusayama, Sakurai and Suzuki (1957) made MOD castings with two investments. They compared the effect of using four differently sized steel casting rings, with and without one layer of asbestos lining, on the size of castings as compared with the wax patterns. All castings made in unlined rings were greatly undersized but this effect decreased with smaller casting rings. This observation suggested that an increasing percentage expansion occurred as the ring size decreased.

Palmer, Roydhouse and Skinner (1961) invested an Invar cube in unlined and lined casting rings. One hour after investing the

cylinder of investment was removed from the casting ring and trimmed to expose the cube face. When a ring liner was used a well defined crevice appeared between the cube and the investment which the authors presumed was the result of the setting expansion of the investment. No crevice was observed when the ring was unlined. This paper again confirms that investment setting expansion is physically inhibited by the rigid casting ring and emphasizes the need for a casting ring liner to provide a cushion for the expanding investment.

Shell and Hollenback (1965b) modified the vitreous silica cylinder expansion equipment first described by Hollenback and Rhoads (1960c), so that both lateral and longitudinal setting and thermal expansions of investments could be determined. When no liner was used in the casting ring the lateral setting expansion of a cristobalite investment one hour after the beginning of mixing was 0.03 per cent and the longitudinal expansion was 0.08 per cent. This expansion was comparable with that recorded when a short liner (3mm short at either end of the casting ring) was used but the expansion was more than seven times greater when a full length liner was used in the ring. At 700°C the lateral thermal expansion in an unlined ring was 0.58 per cent and 1.32 per cent in a longitudinal direction. The corresponding expansion values when a short liner was used were 1.32 per cent laterally and 1.07 per cent longitudinally. With a full-length liner the thermal expansion values became 1.88 per cent laterally and 2.09 per cent longitudinally. The authors concluded that when the casting ring was not lined the total investment expansion was much less in absolute values and at high temperatures the longitudinal expansion was greater than the transverse expansion because of the restrictive effect of the casting ring.

Shell (1969) investigated the effect of unlined casting rings on the expansion of investments by an experimental method previously described (Section 1.6.4, p.68). This invested vitreous silica cylinder method allowed measurements to be made of any enlargement of the mould cavity occurring in a lateral direction. Unfortunately the apparatus did not allow a contraction of the mould cavity to take place, so any potential reduction which could have resulted from an inwardly directed investment expansion could not occur. This would have been recorded simply as a zero dimensional change.

Shell found that the setting expansion of investments in unlined casting rings was completely eliminated and there may have been some potential shrinkage which could not be measured. Two cristobalite investments registered zero thermal expansion at 260°C; however during further heating to 700°C a thermal expansion was observed ranging from 0.70 per cent to 1.30 per cent. Shell noted that cristobalite-containing investments had a larger thermal expansion at 260°C than the casting ring which caused the investment to press towards the centre of the mass. He stated that this inward pressure could deform the mould cavity and recommended that casting ring liners whether used as full length liners or short at either end of the ring should be employed in all casting techniques as they eliminated the observed reduction in expansion.

Jones and Wilson (1970) compared the setting expansion of five gypsum-bonded investments under different conditions of restraint (Section 1.6.1, p.50). The expansion was measured in unlined metal rings, on specimens which were unrestrained during setting and in moistened asbestos lined rings. The values for the setting expansion

in asbestos lined rings were from three to six times greater than those determined when measured in unlined metal rings.

While a large variation exists in the methods which were used by these various workers to determine the restrictive effect of unlined casting rings on investment setting and thermal expansion, their findings all confirm the need for a liner or "cushion" in the casting ring.

#### 1.8 ALTERNATIVE RING LINING MATERIALS

Recent reports have stated that the asbestos fibres in the casting ring liners can cause asbestosis or mesothelioma (Priest and Horner, 1980). In 1976 an acceptable threshold limit value of five fibres/mL of air was set at the American Conference of Industrial Hygienists, for the use of asbestos-containing materials (Yli-Urpo, Øilo and Syverud, 1982).

This limit can be considerably exceeded when castings are removed from asbestos lined casting rings (Brune, 1980). As a result, alternatives to asbestos liners have been introduced. These include absorbent cellulose and non-absorbent ceramic materials.

Because of their recent introduction there are only limited data on the effects of cellulose and ceramic liners on investment expansion and casting accuracy, when compared with the extensive literature devoted to the effect of asbestos liners.

Cellulose readily absorbs water when immersed and therefore, like asbestos, must be wetted before use. This causes a greatly increased setting expansion, of about the same magnitude as when wet asbestos is used (Earnshaw, 1982). Conversely, ceramic liners are virtually non-absorbent when immersed in water under atmospheric pressure and can therefore be used dry.

In 1978, Steinbock and Asgar compared the fit of crowns made with asbestos liners 0.67 mm thick and with ceramic liners 1.03 mm thick. The authors commented on the different handling characteristics of the ceramic material, in particular its much greater elastic recovery after compression and its much lower water absorption. Sets of castings were made with each of the liners, refitted on their dies, embedded in epoxy resin and sectioned. Discrepancies in fit were measured with a travelling microscope, and the authors found no significant difference in dimensional accuracy in castings made with the two different liners.

Nagasawa, Ito, Takahashi et al. (1975) compared the compressibility of ceramic and asbestos lining materials. To investigate their relative cushioning ability they subjected both materials, dry and after water immersion, to compressive stresses up to  $3.0 \text{ kg/cm}^2$ . They reported that asbestos could be compressed by only 10 per cent of its original thickness when dry, and 30 per cent when wet. They suggested that the 30 per cent compressibility provided by the wet asbestos would allow the investment to expand freely during setting. The asbestos would be dried in the early stages of mould burn-out, and they considered that 10 per cent compressibility was not enough for full thermal expansion of the

investment. The ceramic liner, whether tested dry or after immersion, could be compressed to 50 per cent of its original thickness and therefore was considered to be a more acceptable cushioning material.

Takahashi (1979) reported the results of measurements of water absorption of the two materials. He cut strips 35 mm x 90 mm, representing typical ring liners, and found that while the asbestos specimens absorbed 0.6 g of water on immersion for 1 min, the ceramic liners, even after 1 h immersion, absorbed only 0.03 g. From these findings the author concluded that the use of ceramic liners would eliminate the hygroscopic expansion effect seen with wet asbestos.

Earnshaw (1982) developed equipment for measuring investment setting and thermal expansion by continuous measurement on the one specimen, which set in contact with various casting ring liners, and made a series of tests on one widely used inlay casting investment, Kerr Cristobalite. Control specimens setting in contact with a dry neutral lining (modelling wax) gave a setting expansion of 0.4 per cent, and a thermal expansion of 1.3 per cent (total expansion 1.7 per cent). Both wet asbestos and wet cellulose liners caused an increased setting expansion and a reduced thermal expansion with a total expansion of 2.2 to 2.3 per cent. When the water content of the absorbent liners was varied this significantly affected the setting expansion of the investment. The dry ceramic liners caused a setting expansion slightly above that of the control specimens. This was coupled with a slightly reduced thermal expansion to give a total investment expansion of 1.6 to 1.7 per cent. Least reproducible results occurred with the wet liners even when the degree of wetting

was standardized. These results suggest that the use of dry ceramic liners may require an investment whose composition has been adjusted to give a greater total expansion.

In 1982, Gil, Moore and Dykema also studied the effect of asbestos, cellulose and ceramic casting ring liners. In this study full crown castings were made using injection moulded wax patterns which were vacuum invested with a gypsum-bonded investment. Casting rings were lined with single and double layers of the different materials; following manufacturers' instructions asbestos and cellulose were wetted, while the ceramic liners were used dry.

The castings were fitted on their dies, embedded in epoxy resin and sectioned along two planes so that gap distances could be measured at eight stipulated points. It was found that the dry ceramic liner produced very inconsistent castings which were considered clinically unacceptable. The authors noted that this problem was probably related to the use of vacuum investing. When the ceramic liner was saturated with a dilute wetting agent prior to investing, the resultant castings were not significantly different from those obtained with wet asbestos. The fit of castings made with asbestos, one layer of cellulose and one layer of wet ceramic liner were considered acceptable while some of the castings made with two layers of cellulose were regarded as only fair. A single layer of wet asbestos however yielded the best overall fit. A double layer of asbestos also gave well-fitting castings while a double layer of cellulose did not. This difference in the two absorbent liners could be attributed to the lower compressibility of the cellulose liners coupled with their ability to absorb a considerable quantity of

water. The authors concluded that both cellulose and ceramic liners could produce satisfactory castings provided there were some alterations made to the investing technique which had been routinely used with asbestos materials.

Khatchaturian and Caputo (1982) also compared asbestos and a ceramic liner by assessing the accuracy of castings. Unlike Gil, Moore and Dykema, these workers used measured wax patterns, and measured the subsequent castings. This method eliminated the variables introduced by the use of impression materials and die stones. Unfortunately the authors did not describe the investing technique, in particular not stating whether they employed vacuum investing. Nine measurements were made of each of 30 wax patterns and subsequent castings using a travelling microscope. Fifteen of the castings were made with each type of liner. A single layer of each liner was used but their thickness was not given. Statistical analysis of variance revealed that there was no significant difference between the castings made with the two types of liners at the 95 per cent confidence level.

The authors concluded that the use of ceramic fibre materials for casting ring liners did not compromise the accuracy of castings and that these materials could be used as a substitute for asbestos.

The cushioning ability of asbestos and ceramic liners was investigated by Nasu and Noguchi (1982). Results of their compressibility tests agreed with the earlier findings of Nagasawa et al. (1975) already discussed. Continuing this study, Nasu and Noguchi constructed a sophisticated device for measuring the setting

and thermal expansion of the investment mass in a lateral direction in a casting ring, and also the effective total expansion of mould cavities within the ring. They used an unlined ring, and then one and two thicknesses of asbestos, both wet and dry, and one and two thicknesses of dry ceramic liners.

Amongst their conclusions they stated that two thicknesses of dry ceramic liner allowed unrestricted expansion of the investment within the casting ring, that wet asbestos liners increased the setting expansion of the investment but did not provide any cushioning for thermal expansion, and that in general, if the cushioning effect of the liner was not enough to allow free expansion of the investment, a shrinkage of the mould cavity resulted.

Warfield, Lipson and Priest (1982) compared two ceramic liners with asbestos and also concluded that ceramic liners were a suitable substitute. Full crown castings were seated on their dies, embedded in poly(methyl methacrylate) and sectioned. The occlusal gaps between the casting and die were measured at two points. The mean gap distances for the liners were: asbestos 0.24, Kaoliner\* 0.18 and R-Liner\*\* 0.26  $\mu\text{m}$ . According to a one-way analysis of variance the differences between the liners were not found to be statistically significant. Accordingly the authors questioned the continued use of asbestos as a casting ring liner.

Yli-Urpo, Øilo and Syverud (1982) compared the effects of asbestos, cellulose and ceramic liners on the fit of full crown

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\* Dentsply

\*\* Whip-Mix

castings. They gave the thicknesses of the various liners as: asbestos 0.72 mm dry, 0.88 mm wet; cellulose 0.44 mm dry, 0.73 mm wet (a very large increase in thickness after wetting); ceramic 1.35 mm dry, 1.46 mm wet (much thicker than the other two materials). They did not give any details of the method of wetting the liners nor of the way thickness was measured; they did, however, comment that the cellulose material burned at temperatures of 600°C and above.

They made gold alloy full crown castings to fit shouldered steel dies, using a gypsum-bonded investment with water bath immersion and a phosphate-bonded investment setting in air. The mixed investments were subjected to vacuum for 30 s, and investing was performed at atmospheric pressure. Casting accuracy was assessed by measuring the gap between the gingival margin of the casting and the shoulder of the die. As a result of this study, they reported that the ceramic liners gave the most uniformly accurate castings with the gypsum-bonded investment, and that asbestos and ceramic liners gave castings of similar accuracy with the phosphate-bonded investment. They also found that with both investments the cellulose material gave the least accurate and most variable castings. Their conclusion was that the ceramic material was not only an adequate substitute for the traditional asbestos liner, but that it represented an improvement in the casting technique.

Based on the limited data published on the suitability of ceramic liners it would appear that this material may be a suitable substitute for asbestos provided the standard technique of investing wax patterns under vacuum is modified.

Wetting ceramic liners by immersion does not significantly increase their thickness because of their non-absorbent nature. Therefore their use eliminates the hygroscopic expansion effect seen with absorbent liners such as cellulose and asbestos. In addition, at present there is very little data to indicate whether these liners do in fact absorb water out of the investment mass when used with a vacuum.

Based on these facts and the unpredictable results obtained with cellulose liners, neither of these materials can as yet be considered as a suitable substitute for asbestos, in particular when they are used with a standard vacuum investing technique.

## CHAPTER TWO

### PURPOSE AND SCOPE OF THE INVESTIGATION

An important prerequisite in the construction of clinically acceptable cast restorations is a sound knowledge of the physical properties of the various materials employed. For over 50 years the use of a wet asbestos liner in the casting ring has been recognised as an essential part of most casting techniques. The cushioning ability of wet asbestos and the effect of the added water in the wetted liner on the effective W/P ratio of the investment mix, and therefore on the subsequent setting and thermal expansion of the investment, have been extensively investigated. It is now recognised that these are important factors in determining the final mould size and therefore the accuracy of the casting.

Recently, objections to the use of asbestos products have resulted in the introduction of two alternative materials for casting ring liners. These are an absorbent cellulose paper designed to be used wet and a non-absorbent ceramic material based on kaolin wool, intended to be used dry.

The limited data on the suitability of cellulose as a substitute for asbestos have shown that cellulose burns at temperatures of 600°C and above (Yli-Urpo, Øilo and Syverud, 1982) and that it does not provide an adequate cushion even when two layers are used, because of its low compressibility (Gil, Moore and Dykema, 1982).

Conversely, ceramic liners have very different properties as they are non-absorbent, thus eliminating the added water effect associated with absorbent liners, and exhibit a much greater compressibility under load so providing a superior cushioning ability (Steinbock and Asgar, 1978).

The purpose of this investigation was to examine the relationship that exists between the type of casting ring liner used and the dimensional accuracy of full crown castings. The materials tested were three asbestos, three cellulose and five ceramic liners. A standardized vacuum investing technique was used with all the liners. The thickest ceramic liner was also tested without an applied vacuum, to determine the effect of the vacuum on the effective W/P ratio of the investment and the fit of the castings.

A minor study was made on the effect of annealing wax patterns in the production of dimensionally stable patterns for this investigation.

In addition, the thickness of the liners, dry and wet, and their ability to absorb water were measured. The effect of these properties on the effective W/P ratio of the investment mix was also investigated.

It was hoped that as a result of this investigation a lining material could be recommended, coupled with a suitable investing technique which would produce consistently acceptable full crown castings.

## CHAPTER THREE

### MATERIALS AND EQUIPMENT

In this study, wax patterns were made in Kerr Blue Inlay Casting Wax (Regular)\*, batch number 022884 1306. This is classified as a Type C Class 1 wax, suitable for indirect wax patterns (ADA Specification No.4, 1974). Patterns were invested in Kerr Cristobalite Inlay investment\*\*, batch number 1137, mixed with distilled water in a W/P ratio of 0.40. Eleven different ring liners were used representing asbestos, cellulose and ceramic materials. These are listed in Table 3.1.

Most of these liners were supplied in rolls, marketed by dental companies and intended specifically for casting small dental restorations. The exception was Triton Kaowool, an industrial ceramic paper supplied in sheets and intended for high temperature thermal insulation. It is available in various thicknesses; in this investigation ring liners were cut from sheets nominally 1 mm and 2 mm thick.

Wherever possible, liners were cut to a size of 95 mm x 33 mm, so that they could be positioned 2.5 mm short of each end of the ring. Some rolls were supplied in widths less than 33 mm (Table 3.1). In these cases the full width of the roll was used, and the liner positioned symmetrically in the ring.

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\* Sybron/Kerr, Laboratory Products Division, Emeryville, California, U.S.A.

\*\* Sybron/Kerr Products, Romulus, Michigan, U.S.A.

Table 3.1

## LINING MATERIALS INVESTIGATED

| Type                    | Name                             | Code | Width<br>of<br>Strip<br>(mm) | Batch No | Manufacturer                                                                     |
|-------------------------|----------------------------------|------|------------------------------|----------|----------------------------------------------------------------------------------|
|                         | G.C. Asbestos Ribbon             | GA   | 32                           | 100921   | G.C. Dental Ind. Corp, Japan                                                     |
| Asbestos<br>(used wet)  | Kerr Strip Asbestos              | KA   | 33                           | -        | Sybron/Kerr Products,<br>Romulus, Michigan, U.S.A.                               |
|                         | Shofu Asbestos Ribbon            | SH   | 29                           | 038302   | Shofu Dental Mfg. Co., Kyoto,<br>Japan                                           |
|                         | Austenal Ring Liner              | AU   | 33                           | -        | Howmedico Inc., U.S.A.                                                           |
| Cellulose<br>(used wet) | Bego Mould inlay Strip           | BE   | 33                           | -        | Bego Bremer Goldschlägerei<br>Bremen, West Germany                               |
|                         | Whip-Mix Liner<br>(Non-Asbestos) | WM   | 29                           | -        | Whip-Mix Corp., Louisville,<br>U.S.A.                                            |
|                         | Dentsply Kaoliner                | DE   | 32                           | 111578   | Dentsply Int. Inc., York,<br>U.S.A.                                              |
|                         | G.C. Casting Liner               | GC   | 32                           | 021121   | G.C. Dental Ind. Corp., Japan                                                    |
| Ceramic<br>(used dry)   | Kerr Flask Liner                 | KF   | 30                           | 021583   | Sybron/Kerr Products,<br>Romulus, Michigan, U.S.A.                               |
|                         | Triton Kaowool<br>(1 mm)         | K1   | 33                           | -        | Morganite Ceramic Fibres Pty.<br>Ltd., Alexandria, New South<br>Wales, Australia |
|                         | Triton Kaowool<br>(2 mm)         | K2   | 33                           | -        |                                                                                  |

In accordance with manufacturers' instructions, the asbestos and cellulose liners were wetted before use, while the ceramic liners, which are normally non-absorbent, were used dry.

In all cases mechanical mixing under vacuum was used, a 300 mL Whip-Mix Vac-U-Spat Investor\* being driven by a Whip-Mix Combination Unit. Low speed mixing was preferred, as timing was less critical and overspatulation unlikely. For this reason the Vac-U-Spat Investor was modified by changing the chuck, so that it could be used on the low speed shaft of the Combination Unit. This has a rotational speed of 425 r/min.

The casting rings were Kerr Flasks No.1C, 30 mm inside diameter and 38 mm high. These are available in cartridge brass or stainless steel; in this investigation brass rings were used as although they are less heat-resistant, they have a higher thermal expansion ( $\alpha_{(25 - 300^{\circ}\text{C})} = 19.9 \times 10^{-6}/\text{K}$ , compared with  $16.5 \times 10^{-6}/\text{K}$  for stainless steel). For this reason they were considered more appropriate for use with an investment with a high thermal expansion.

The rings were used in conjunction with a rubber sprue base (Whip-Mix crucible formers No.4081). It was necessary to reduce the outside diameter of the rings slightly to suit the Whip-Mix Vac-U-Spat Investor.

Hollow sprues 12 mm long were cut from hard drawn stainless steel tubing, outside diameter 2.0 mm.

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\* Whip-Mix Corp., Louisville, U.S.A.

Burn-out and heating of the moulds to the casting temperature was carried out in an S.E.S. Model 7 electric furnace\* fitted with a Shinko PC-211 cam type programme controller\*\*. The cam profile was cut to provide a furnace heating rate of 5°C/min from ambient to 200°C, 1°C/min from 200 to 300°C and then 5°C/min from 300 to 650°C.

During burn-out and heat soaking mould temperature was monitored by a nickel-chromium/nickel-aluminium thermocouple whose hot junction was embedded in the centre of a casting ring filled with investment, placed amongst the moulds in the furnace. Thermocouple output was read by means of a Therma 1 temperature indicator\*\*\*.

Castings were made in a Kerr Centrifico centrifugal casting machine<sup>†</sup>. The alloy used was Type B Engelhard G-5<sup>††</sup> and it was melted with an S.S. White No.7 blowtorch<sup>†††</sup>, burning a mixture of mains gas and air.

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\* Scientific Engineering Services, Australia.

\*\* Shinko Electric Instrument Co. Ltd., Osaka, Japan.

\*\*\* Duff and Macintosh Pty. Ltd., Crows Nest, Australia.

† Sybron/Kerr Products, Romulus, Michigan, U.S.A.

†† Engelhard Industries Pty. Ltd., Victoria, Australia.

††† The S.S. White Company of Australia Pty. Ltd., Balgowlah, Australia.

## CHAPTER FOUR

### EXPERIMENTAL METHODS

#### 4.1 AMBIENT CONDITIONS

Except where otherwise noted, all specimens were prepared and all measurements made under ambient conditions controlled at  $21 \pm 1^\circ\text{C}$  and  $55 \pm 5$  per cent relative humidity.

The only exceptions were in annealing wax patterns (Section 4.4, p.102) and in burn-out and casting procedures.

#### 4.2 THE DIE ASSEMBLY

The die used for making wax patterns was machined from Invar. This alloy has a coefficient of linear thermal expansion over the temperature range  $20 - 100^\circ\text{C}$  of less than  $1.7 \times 10^{-6}/\text{K}$  (Braddick, 1954), so that temperature changes which occurred during the making of the wax patterns caused only minimal dimensional changes in the die.

The die was shaped as a truncated cone, with the dimensions given in Figure 4.1; it can be seen that they were similar to those of a full crown preparation on a molar. The taper of 0.6 mm on a height of 6.0 mm gave a ratio of 1:10, so that axial discrepancies, measured at the gingival margins of the wax patterns and the

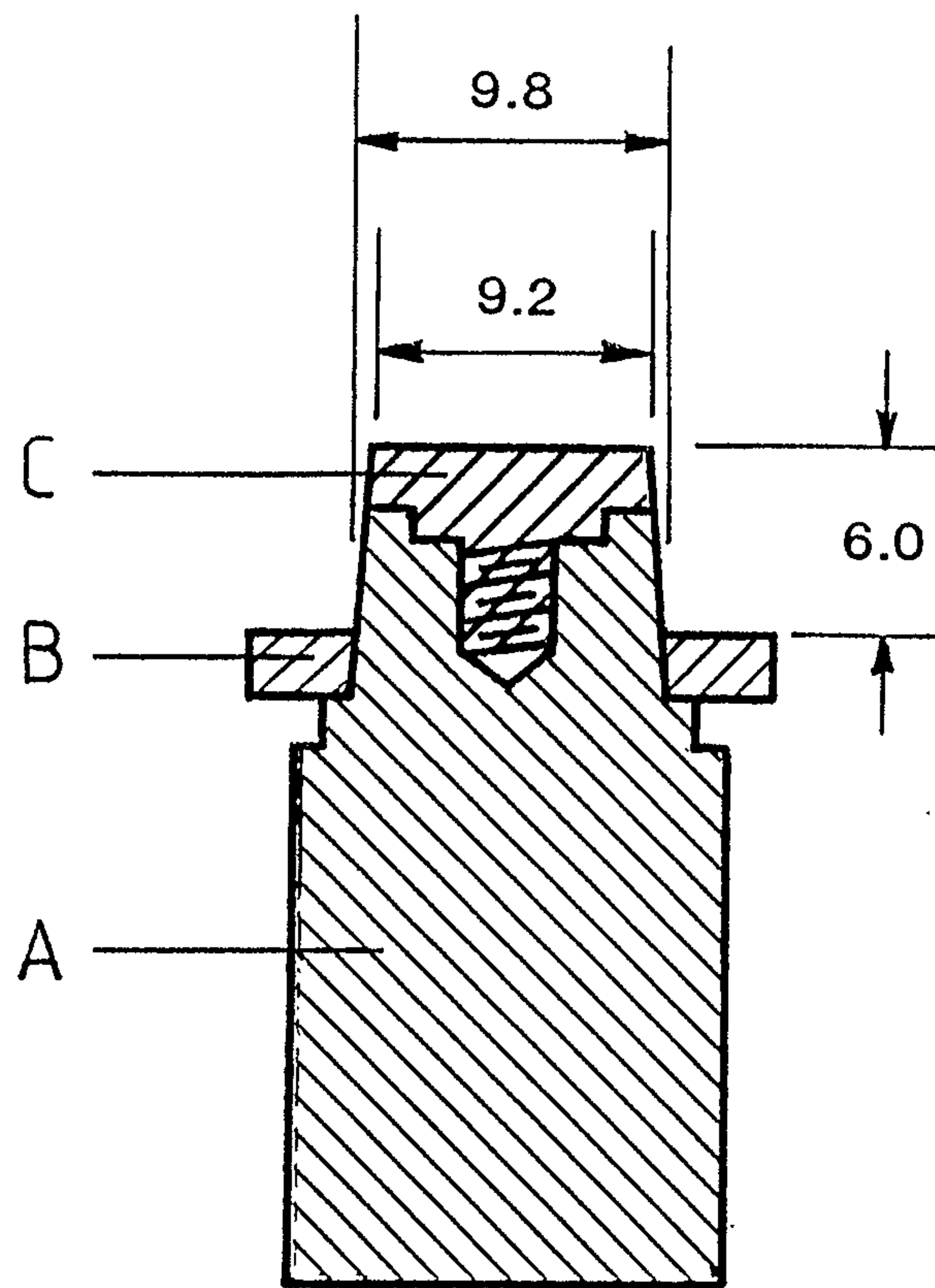


Figure 4.1

The complete die used in this investigation.

- A) The basic die
- B) The removable gingival spacer
- C) The removable occlusal section.

All dimensions are in mm.

resulting castings, were divided by ten to give a measure of the dimensional accuracy of the casting in a diametral direction.

The gingival shoulder of the preparation was represented by a 2 mm thick spacer in the form of a removable washer which fitted accurately on the taper and rested on the shoulder of the die (B, Figure 4.1). The occlusal 2 mm of the die was a separate section, spigotted and threaded into place (C, Figure 4.1).

When the fit of castings was measured both the occlusal and gingival sections of the die were first removed. Thus both oversized and undersized castings could be completely reseated on the taper of the die before being measured.

In preparation for making wax patterns the die was fitted with two sleeves (A and B, Figure 4.2). A third sleeve was fitted over the coronal part of the die so that it rested on the gingival washer (C, Figure 4.2). This sleeve which had an inside diameter of 11.3 mm defined the outer wall of the cylindrical wax pattern which was therefore 0.75 mm thick at the gingival shoulder. The sleeve was 8 mm high so this became the overall height of the wax pattern.

The mould for the wax patterns was completed by a piston which seated on the third sleeve (D, Figure 4.2). An axial hole in the piston 1 mm in diameter allowed the escape of excess wax. The parts of the mould assembly are illustrated in Figure 4.3.

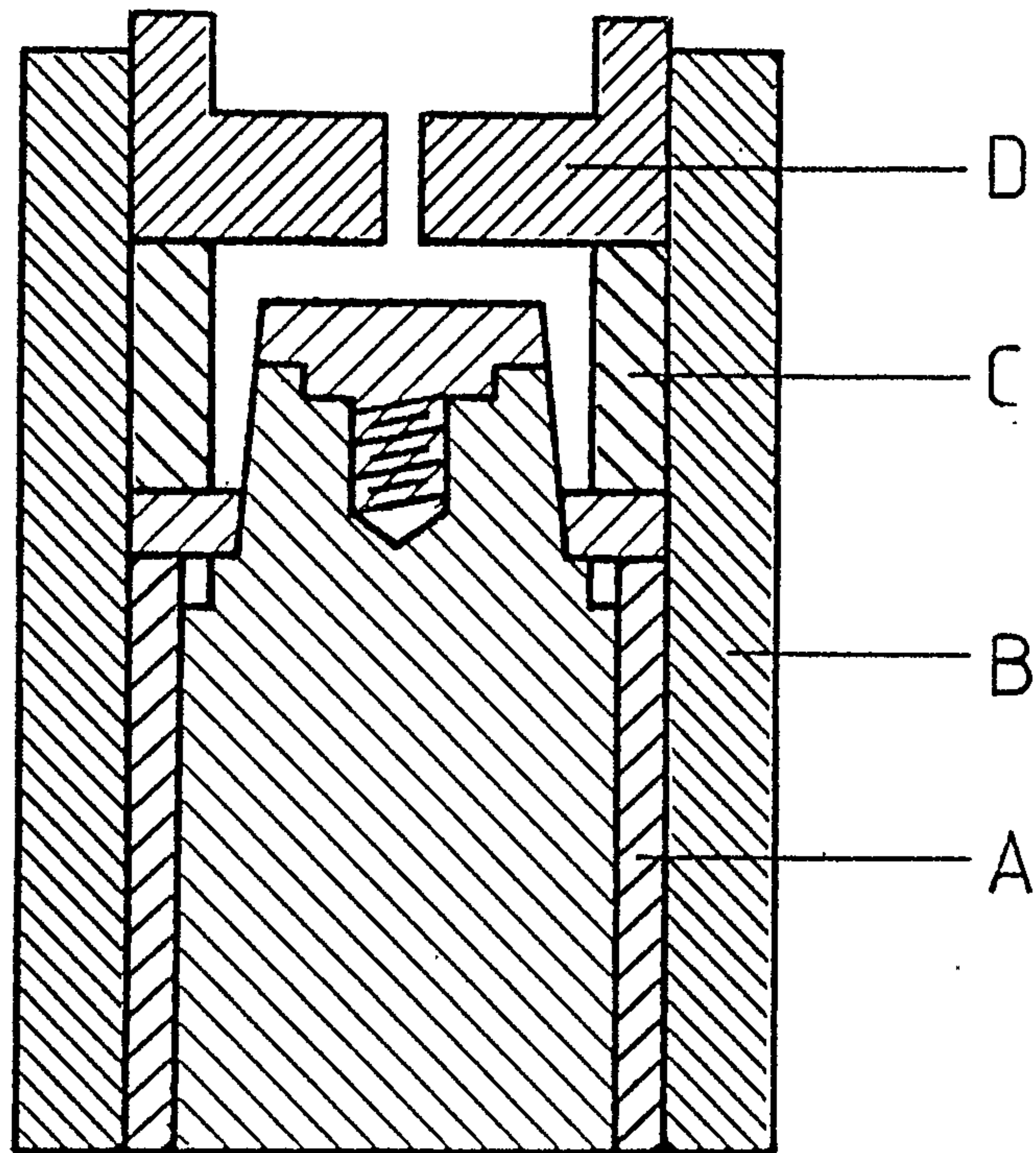


Figure 4.2

The complete mould assembly used for making wax patterns.

- A) Lower inner sleeve
- B) Outer sleeve
- C) Sleeve which defined outer wall of wax patterns
- D) Piston

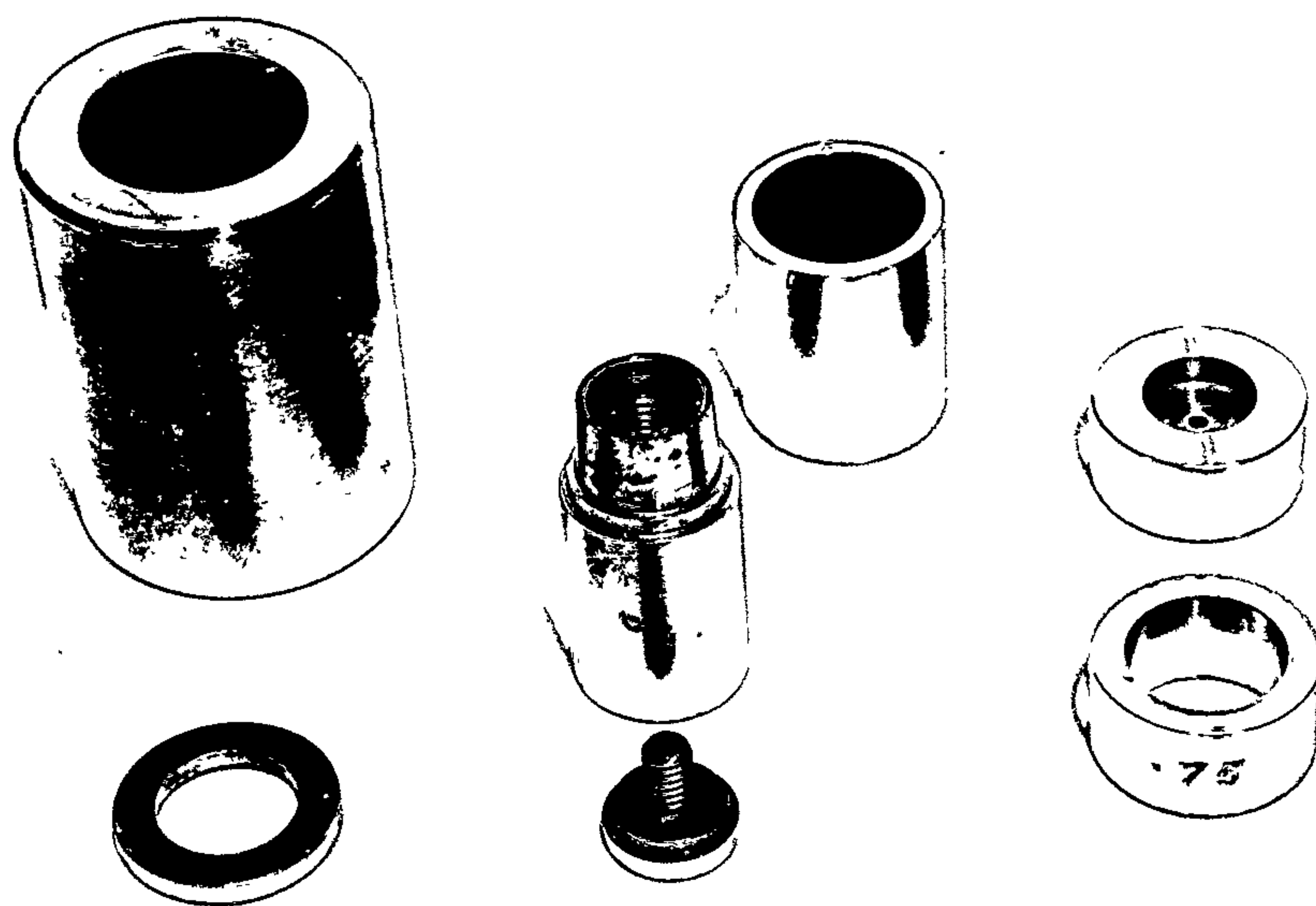


Figure 4.3

Parts of the die assembly used in this study.

### 4.3 FABRICATION OF WAX PATTERNS

The various parts of the mould assembly were sprayed with a silicone mould release agent\*. Inlay Casting wax (Regular) was melted in a small ladle over a Bunsen flame until it formed a mobile liquid. This was poured into the mould space to give a moderate excess, shown by a well-defined positive meniscus (Figure 4.4). As soon as the gloss had completely disappeared from the surface of the wax the piston (D, Figure 4.2) was inserted and forced home by means of a small machine vice. Excess wax was extruded through the vent in the piston (Figure 4.5). The wax by this time was very viscous, and because the vent was narrow, sufficient pressure was developed within the mould space to ensure complete wax patterns. The wax was allowed to solidify under pressure for three minutes.

Then the die assembly was removed from the vice and the outer sleeve (B, Figure 4.2) and piston (D, Figure 4.2) removed. If the piston had not seated completely on the third sleeve as was illustrated in Figure 4.5, the excess wax was carved down flush with the top of the sleeve, with a sharp rigid blade.

Sleeves A and C (Figure 4.2) were then removed and the wax pattern was immediately sprued with a 12 mm long section of 2 mm outer diameter stainless steel tubing, attached axially to its occlusal surface (Figure 4.6).

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\* Rocol PR, Rocol Advanced Lubricants, Australia.

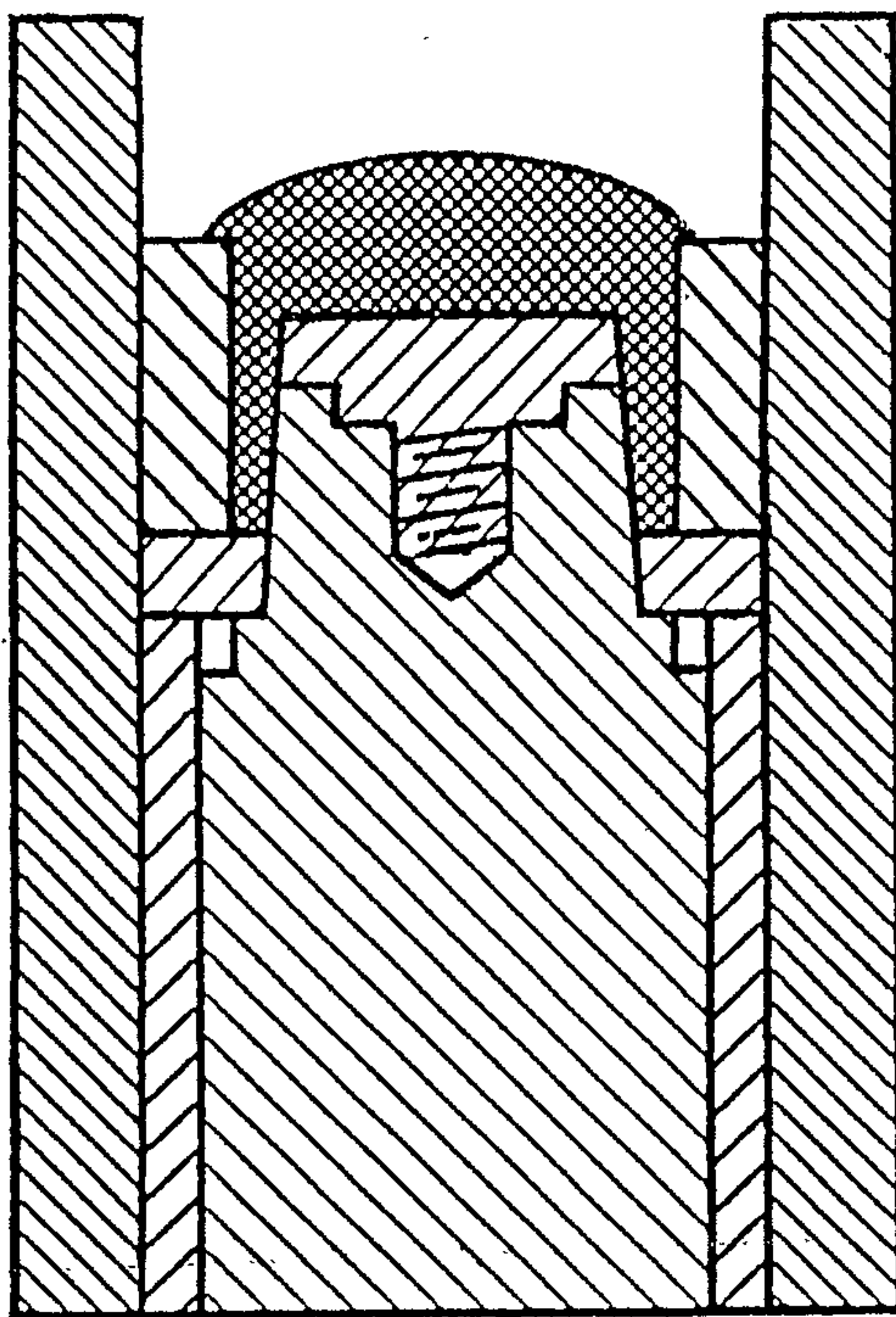


Figure 4.4

Filled mould space showing positive meniscus of liquid wax.

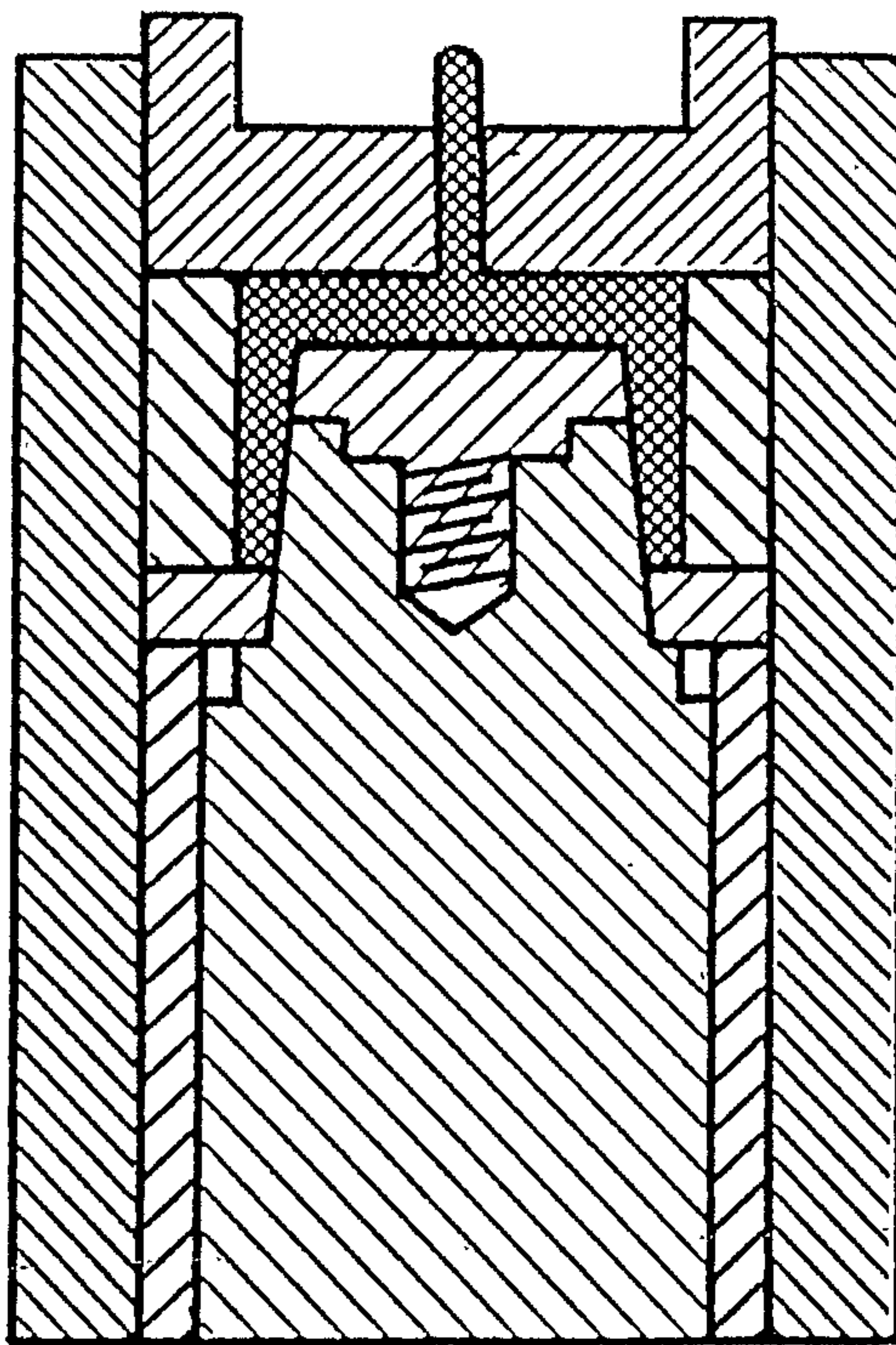


Figure 4.5

Piston in place with excess wax extruded through the vent.

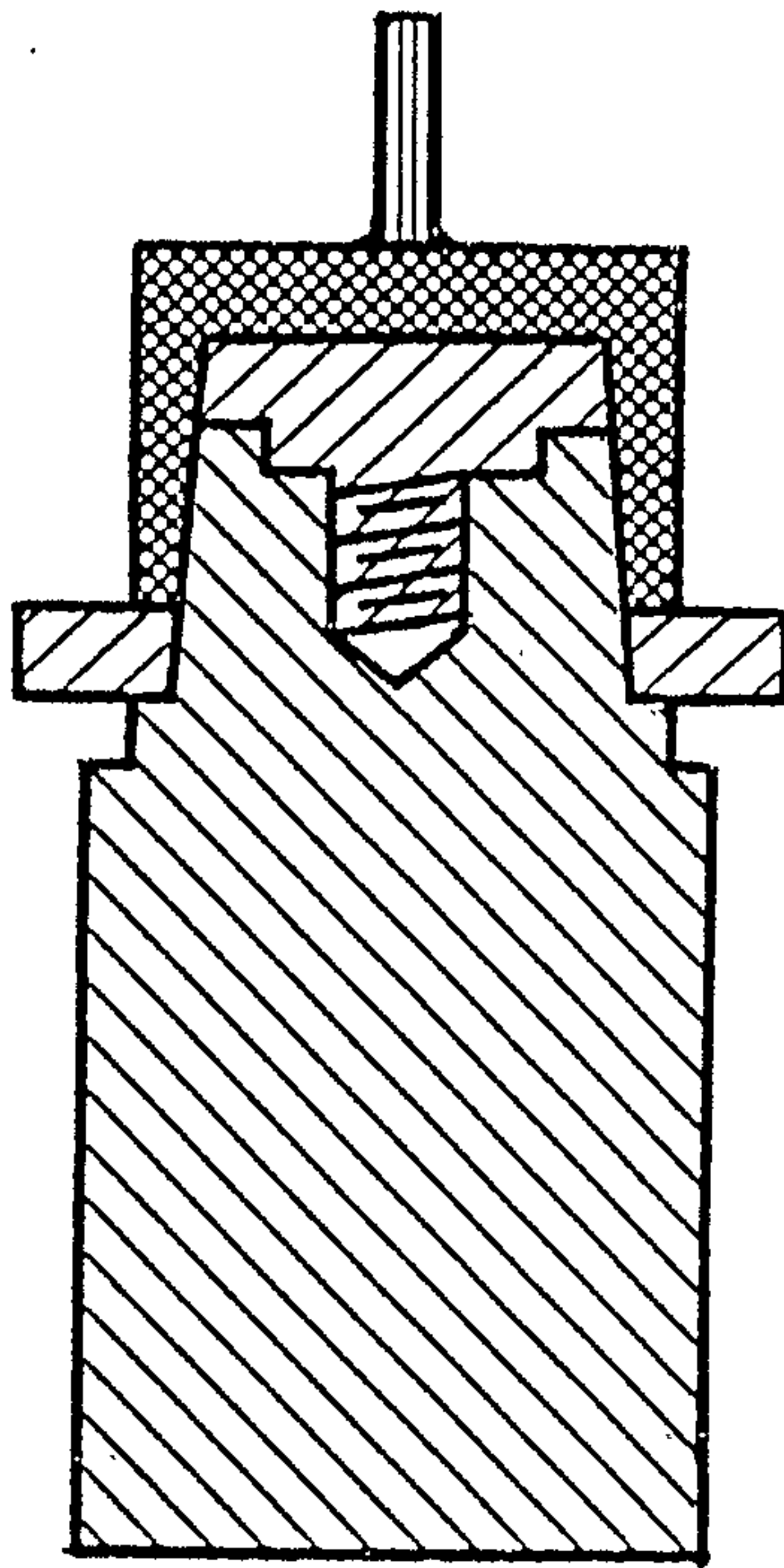


Figure 4.6

Sprued wax pattern.

As six complete die assemblies were available, coded A to E, wax patterns were made in batches of six, and each pattern was identified by scribing the relevant code letter on its outer surface. An index mark was also scribed on the wax pattern to ensure that both the patterns and the castings were replaced in the same position on their respective dies.

#### 4.4 ANNEALING THE PATTERNS

At the beginning of this study, wax patterns were removed from their dies as soon as they were sprued; the gingival washers were lifted off and the patterns immediately replaced for the initial measurements. However it was found that an immediate elastic recovery took place as soon as a pattern was freed from its die, when some of the moulding stresses were relieved. Since these residual moulding stresses were induced for the most part by the prevention of thermal contraction of the cooling pattern by the Invar die, when released they caused a contraction of the pattern, which prevented its complete reseating. A further time-dependent stress relief then occurred which represented delayed elastic recovery and produced a continuing deterioration in the fit of the pattern. As a result, the gap between the gingival margin of the wax pattern and the shoulder of the die slowly increased, and this made reproducible measurements of the gap distance impossible.

A subsidiary study was made, to establish whether wax patterns with better dimensional stability would result from an annealing process carried out before the patterns were removed from their dies.

It was considered that holding the pattern, on the die, at a temperature high enough to allow stress relaxation (i.e., removal of moulding stresses by plastic flow of the wax rather than by immediate and then delayed elastic recovery), for a long enough time, should produce stress-free patterns. Rapid cooling of these patterns from annealing to ambient temperature would however, induce a new set of residual stresses. Therefore it was also considered necessary to cool the annealed patterns, still on their dies, very slowly. It was hoped slow cooling would allow continued stress relaxation, so that the pattern would be still largely stress free at the end of the annealing cycle.

In this subsidiary study it was necessary to assess the fit of wax patterns before as well as after their removal from the dies, and this was made difficult by the presence of the gingival washer. Therefore a second set of dies was made, with the same dimensions as the first, but without detachable sections. The dimensions are shown in Figure 4.7. Sleeves and a piston were used in the same way as with the original dies, to complete a mould, and wax patterns were produced as already described. When the sleeves were removed the marginal fit of the wax patterns on the shoulders of the dies could easily be assessed. In fact it was always found that, before sprued patterns were removed from their dies, there was no measurable marginal gap between pattern and die.

To anneal wax patterns, the sprued patterns on their dies were placed in a laboratory oven maintained at  $40^{\circ}\text{C} \pm 1^{\circ}\text{C}$  for 5 h; the oven was then turned off, so that the temperature fell slowly to ambient. The dies were removed 15 h later.

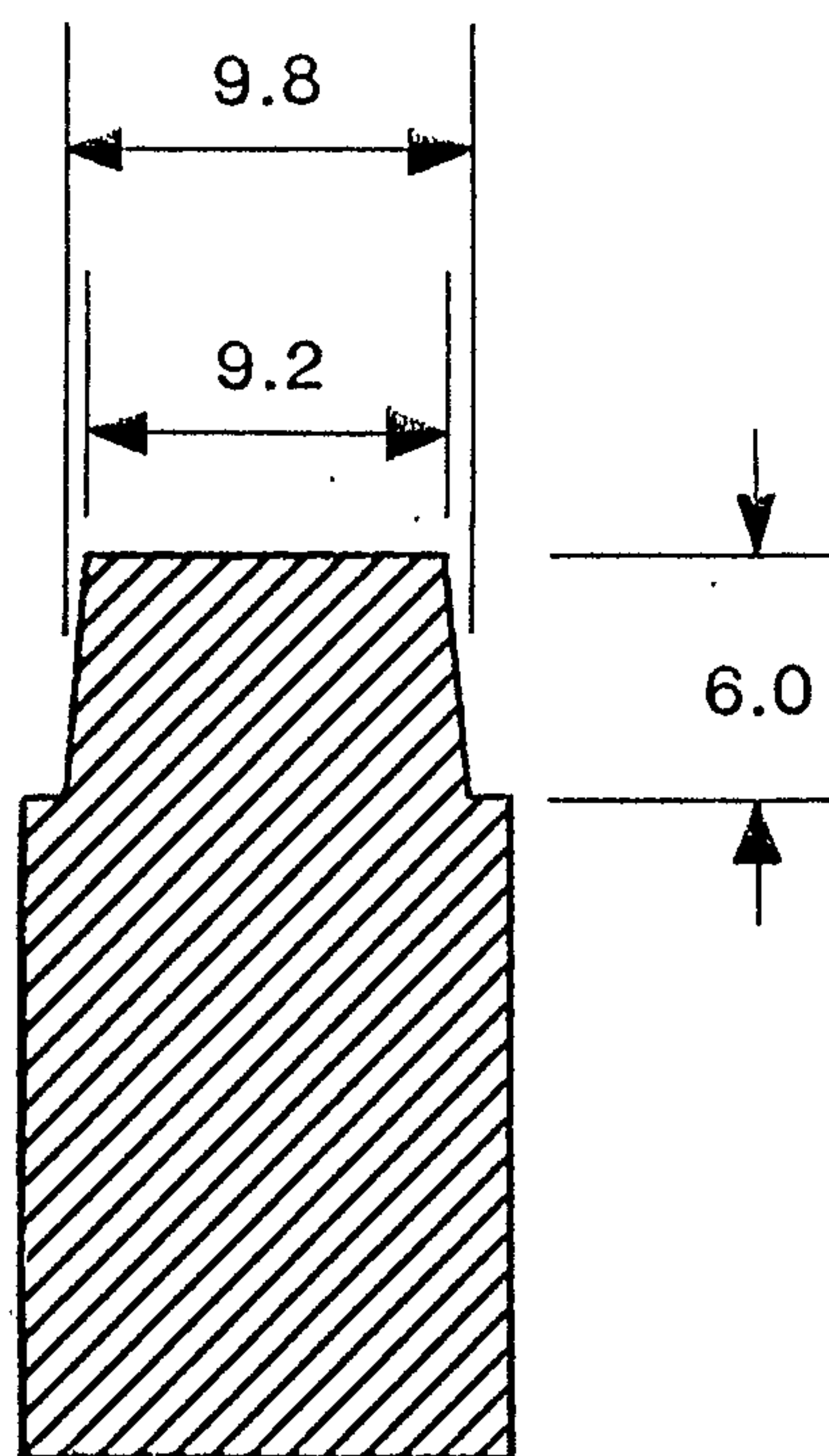


Figure 4.7

The die used in the wax pattern annealing study.

All dimensions are in mm.

This annealing cycle produced stress-free patterns which fitted perfectly back on their dies after removal and which showed no measurable dimensional change even after prolonged standing.

In contrast, patterns prepared in the same way but removed immediately from the die without annealing and reseated under a load of approximately 20 g showed a mean discrepancy of 0.30 per cent. The die used in this part of the investigation and the fit of typical annealed and non-annealed patterns are illustrated in Figure 4.8.

#### 4.5 MEASUREMENT OF WAX PATTERNS

After the annealing process the wax patterns were gently rotated off their dies and the gingival washers removed. The wax patterns were then replaced on their respective dies in correct alignment and seated under a load of approximately 20 g. Since the six dies weighed between 20 g and 23 g, they were used to provide the seating load. After the patterns had been repositioned the dies were inverted and placed on a block counterbored to accommodate the sprue former (Figure 4.9).

Measurements of the distance separating the gingival margin of the pattern and the shoulder of the die were made at four equispaced points around the die with a Beck\* travelling microscope at a magnification of 30 x (Figure 4.10). A jig, clamped to the stage of the microscope, was used to align a V block in which the die rested.

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\* R. and J. Beck Ltd., London.

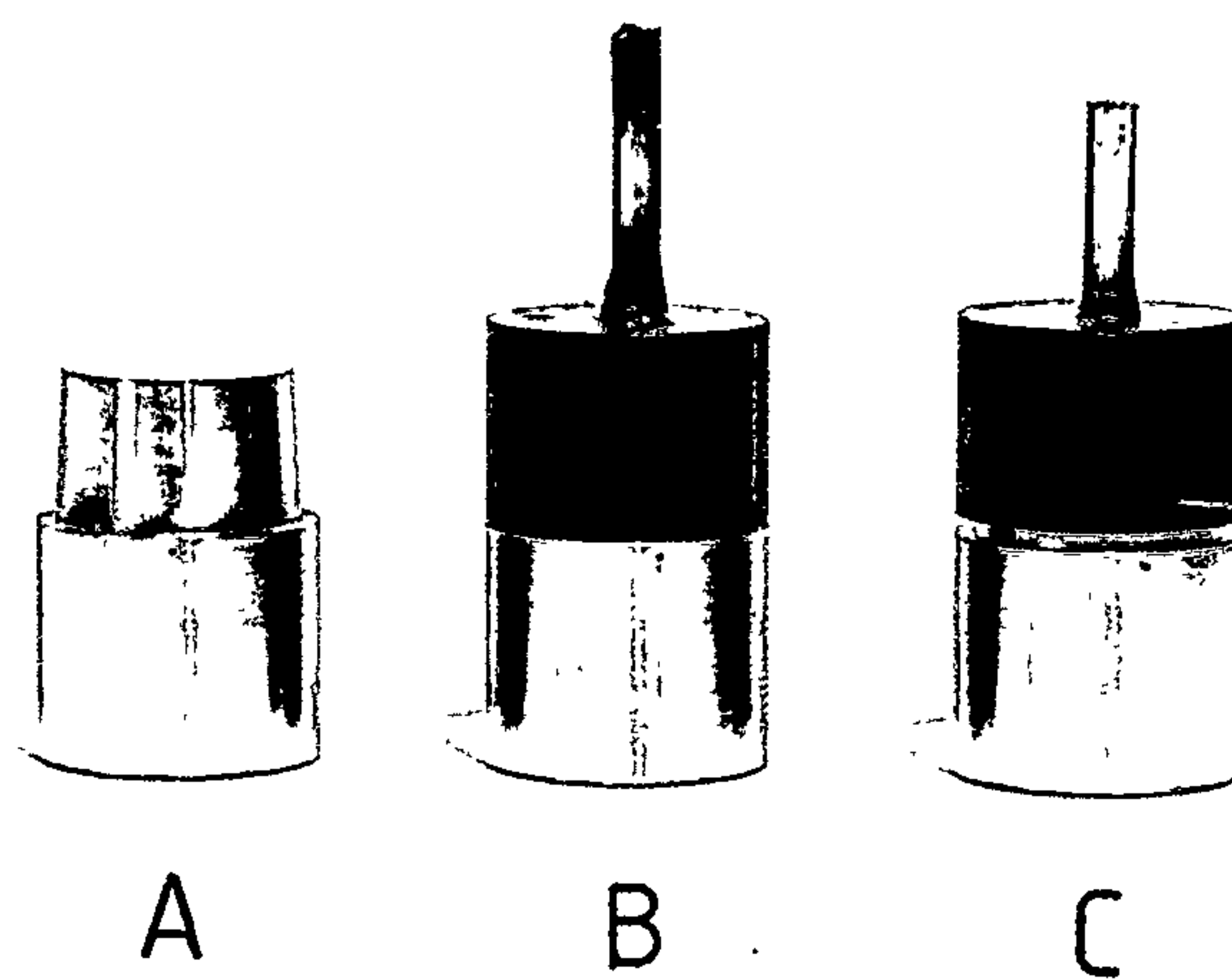


Figure 4.8

- A) The die used in the wax pattern annealing study.
- B) A wax pattern annealed before removal from the die and then reseated.
- C) A wax pattern removed immediately from the die without annealing and then reseated.

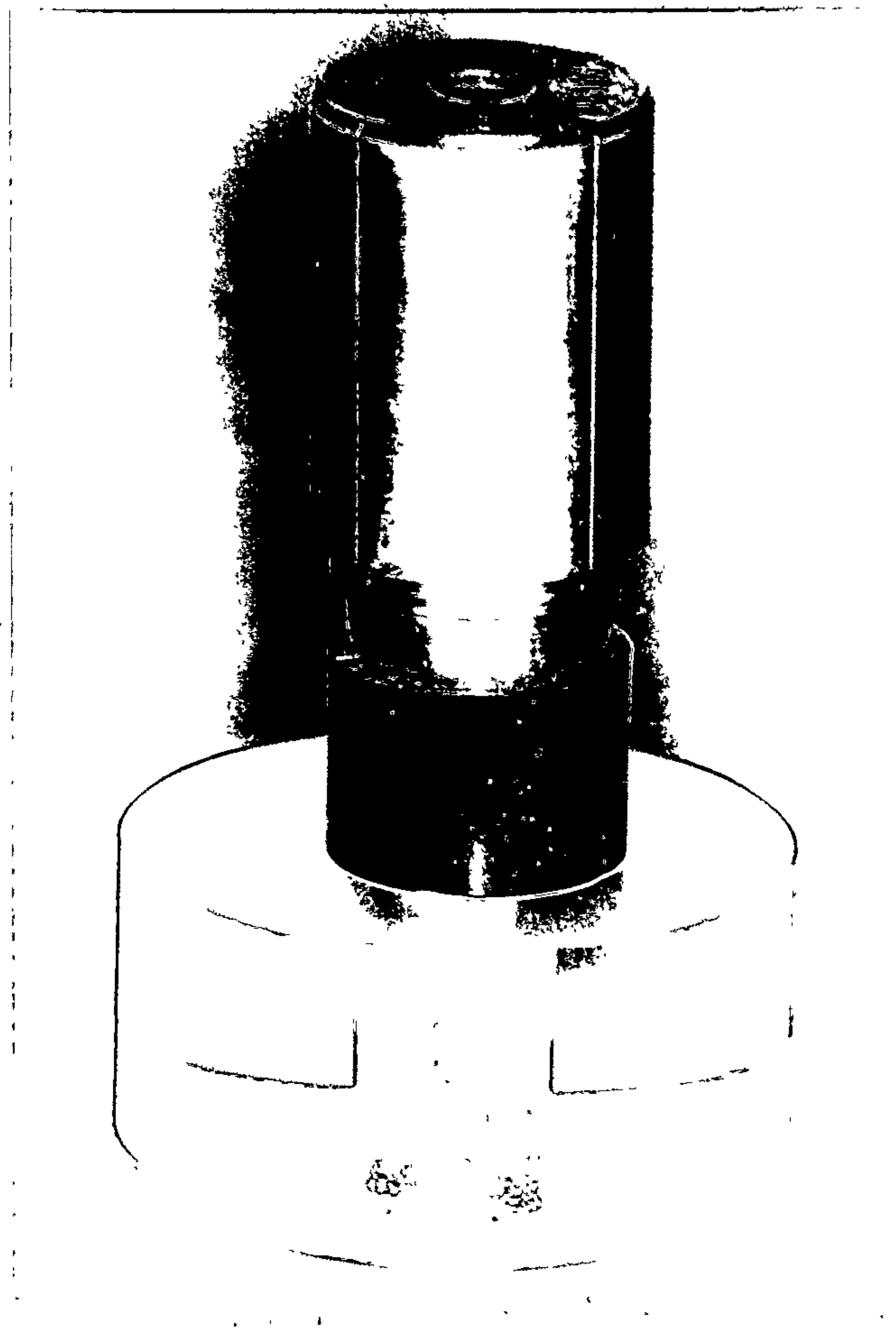


Figure 4.9

The wax pattern reseated under a load of approximately 20g.

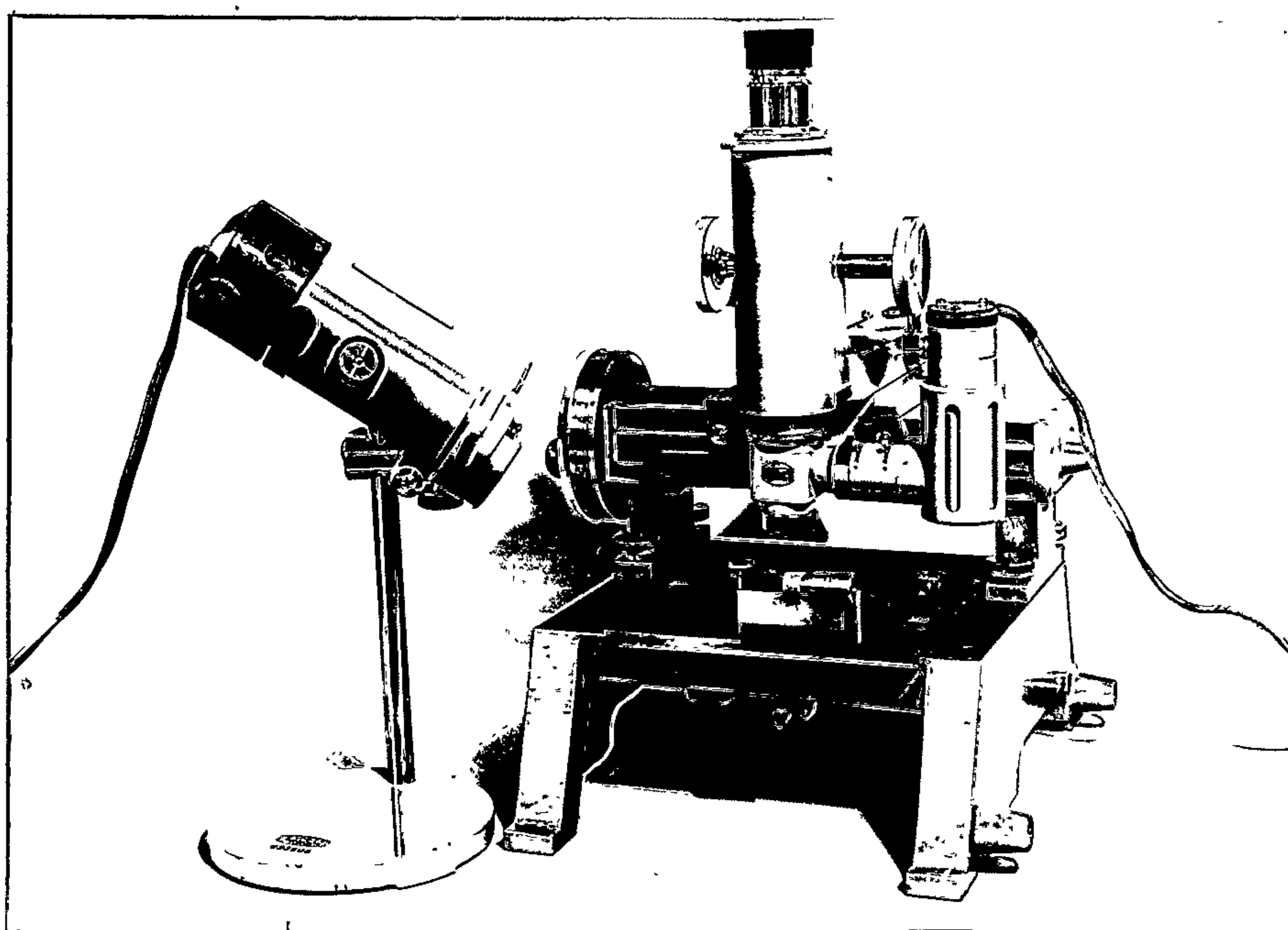


Figure 4.10

The travelling microscope used for measuring the marginal discrepancy.

The combination of jig and V block allowed reproducible positioning of the die and the die could be rotated in the V block without losing its alignment with the direction of travel of the microscope (Figure 4.11). Therefore the same part of the microscope travel was used for all the measurements, thus eliminating random errors. The micrometer drum of the microscope was graduated to 2  $\mu\text{m}$  so that it could be read easily to 1  $\mu\text{m}$  by interpolation. Measurements at each of the four positions were repeated five times and then averaged to give a fiducial value from 40 readings for the marginal gap, and so the fit of the pattern itself (A, Figure 4.12).

Lighting was provided by a combination of oblique illumination from an external light source\* and incident illumination provided by the built-in illuminator on the microscope. Light from the two sources was balanced to provide the best illumination for the measurements.

#### 4.6 INVESTING THE PATTERNS

Except for castings in the control group where no liner was used, the casting ring was fitted with a piece of liner 95 mm in length and between 29 and 33 mm in width (Table 3.1, p.90) depending on the material.

Some of the liners, in the dry state, showed a marked difference in the texture of their two sides, one being smoother than

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\* Olympus Universal Illuminator Model LSD and Transformer Model TC.

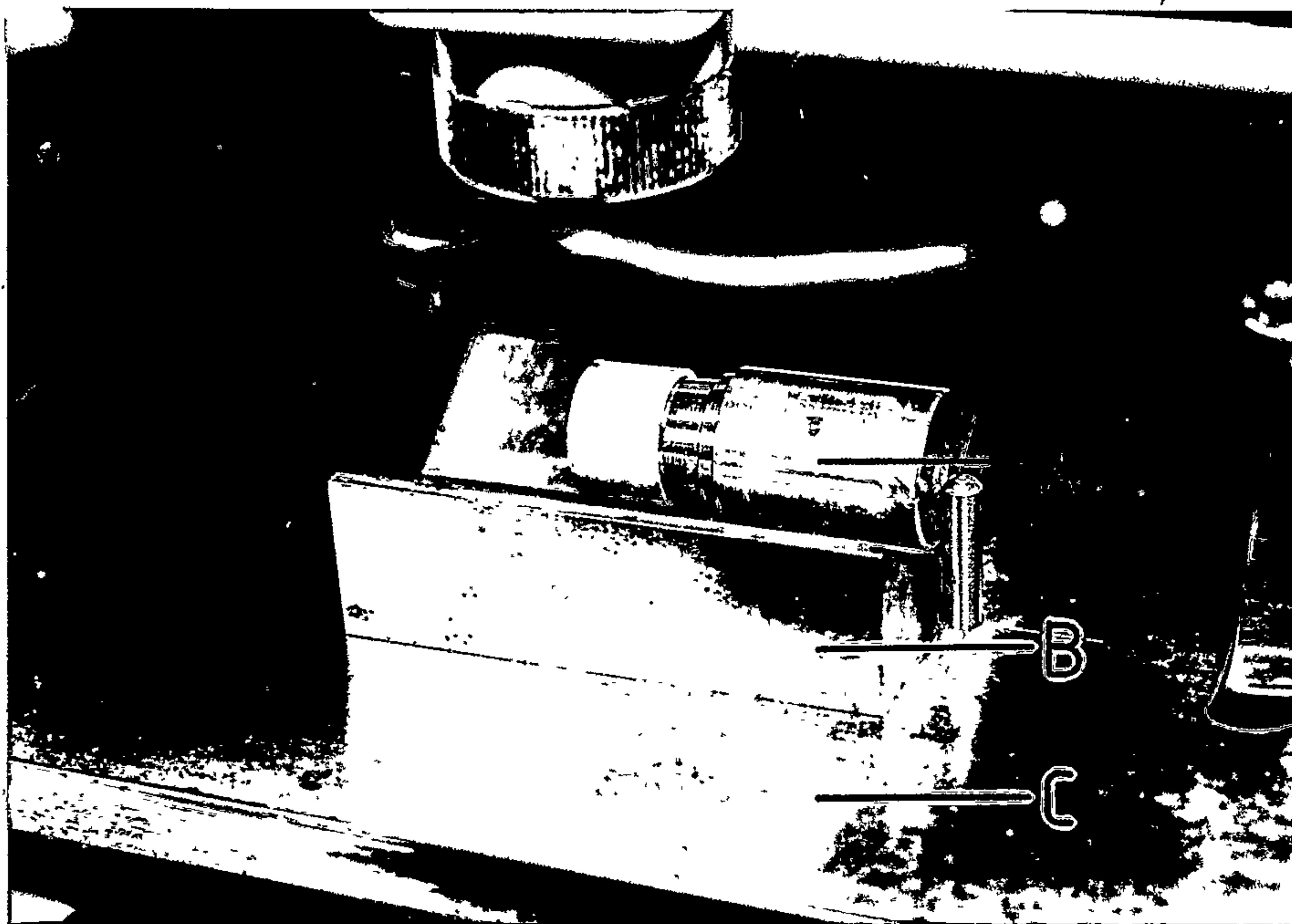


Figure 4.11

The V block used to align the position of the die on the microscope stage.

- A) Die
- B) V block
- C) Aligning jig

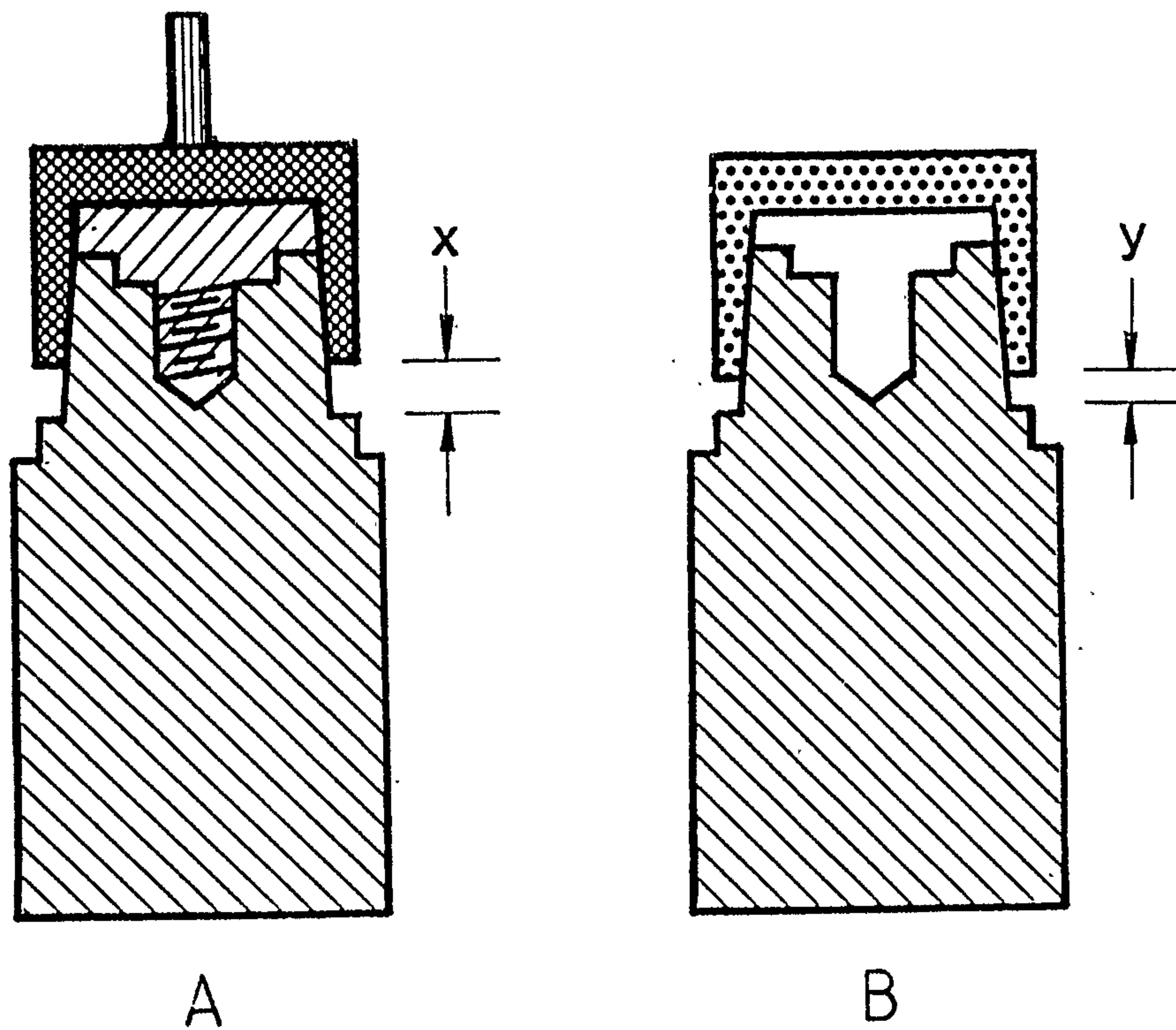


Figure 4.12

The fit of wax patterns and castings.

- A) the distance x represents the marginal gap between the wax pattern and the shoulder of the die.
- B) The distance y indicates the discrepancy between the gingival margin of the casting and the shoulder of the die.

the other. With these materials the liner was positioned with the smoother side towards the investment. Care was taken to centre the liner symmetrically within the ring and it was secured with a small amount of sticky wax.

When absorbent asbestos and cellulose liners were used, the lined rings were weighed to 0.01 g\*. They were then immersed in distilled water for one minute, removed, the external surface carefully dried and when water had stopped dripping from the liner the rings were reweighed. The difference in mass gave a measurement of the water uptake of each absorbent liner.

Sprued patterns were mounted on sprue bases, so that the length of exposed sprue was 6 mm, and the sprue bases were then fitted to the lined casting rings. All patterns were invested within one hour of their first removal from the die.

Kerr Cristobalite Inlay investment was mixed with distilled water in the proportions of 50 g powder to 20 g water (W/P ratio 0.40). Both water and powder were dispensed gravimetrically to 0.01 g\*.

Mixing and investing were performed using the modified equipment described in Chapter Three (p.91). The investment powder and water were mixed by hand in the bowl of the Vac-U-Spat (at a rate of 3 turns/s for 10 s), the Vac-U-Spat and the lined casting ring were

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\* Mettler Balance, Type PC 4400.

assembled and mechanical mixing under vacuum (96 KPa = 720 mm Hg) performed for 20 s. Then the Vac-U-Spat was inverted to invest the pattern, and vibrated under vacuum on the Combination Unit for 30 s. Timing of the mixing procedure followed a standardized programme, and the whole procedure took 1 min 20 s.

This vacuum investing technique was used with all the liners studied. When dry ceramic liners were used it was found that, although at atmospheric pressure these materials when immersed were not wetted and did not absorb any water, during vacuum investing they rapidly absorbed water from the investment mix. This reduced the effective W/P ratio of the mix and so significantly shortened the working time of the investment.

The effect was most marked with the thickest ceramic liner, Triton Kaowool 2 mm (K2). Here the working time became so short that in many cases vacuum investing was not effective, and the subsequent casting had to be discarded because of surface imperfections. Therefore experiments were repeated with this lining material, using mechanical mixing under vacuum as already described but investing by hand under atmospheric pressure. The results obtained in this way are identified by the code K2NV.

#### 4.7 BURN-OUT AND CASTING

The investment was allowed to set for one hour before removal of the sprue base and sprue former.

The moulds were then placed in the cold burn-out furnace and the temperature raised according to the programme given in Chapter Three (p.92). Moulds were heat soaked at a temperature of  $650^{\circ}\text{C} \pm 10^{\circ}\text{C}$  for at least 15 min before the castings were made. The casting machine was wound three turns and approximately 10 g of gold alloy was used for each casting. All castings were completed within 30 s of removal of the mould from the furnace.

The castings were quenched in water after bench cooling for three minutes. They were then scrubbed, pickled in 50 per cent sulphuric acid and ultrasonically cleaned for 10 min in water. Any small nodules on the castings were removed with a scalpel and the sprue and button were removed with a separating disc.

#### 4.8 MEASUREMENT OF CASTINGS

After the gingival and occlusal sections had been removed from the dies, the castings were reseated under an axial load of 2 Kg (Figure 4.13). Marginal gap measurements were then repeated with the travelling microscope using the same jig and illumination system as before.

A reduction in the measurement  $y$  (B, Figure 4.12) compared with the original  $x$  (A, Figure 4.12) gave a positive value for  $x-y$  which indicated that the casting was oversized. Conversely undersized castings gave a negative value for  $x-y$ .

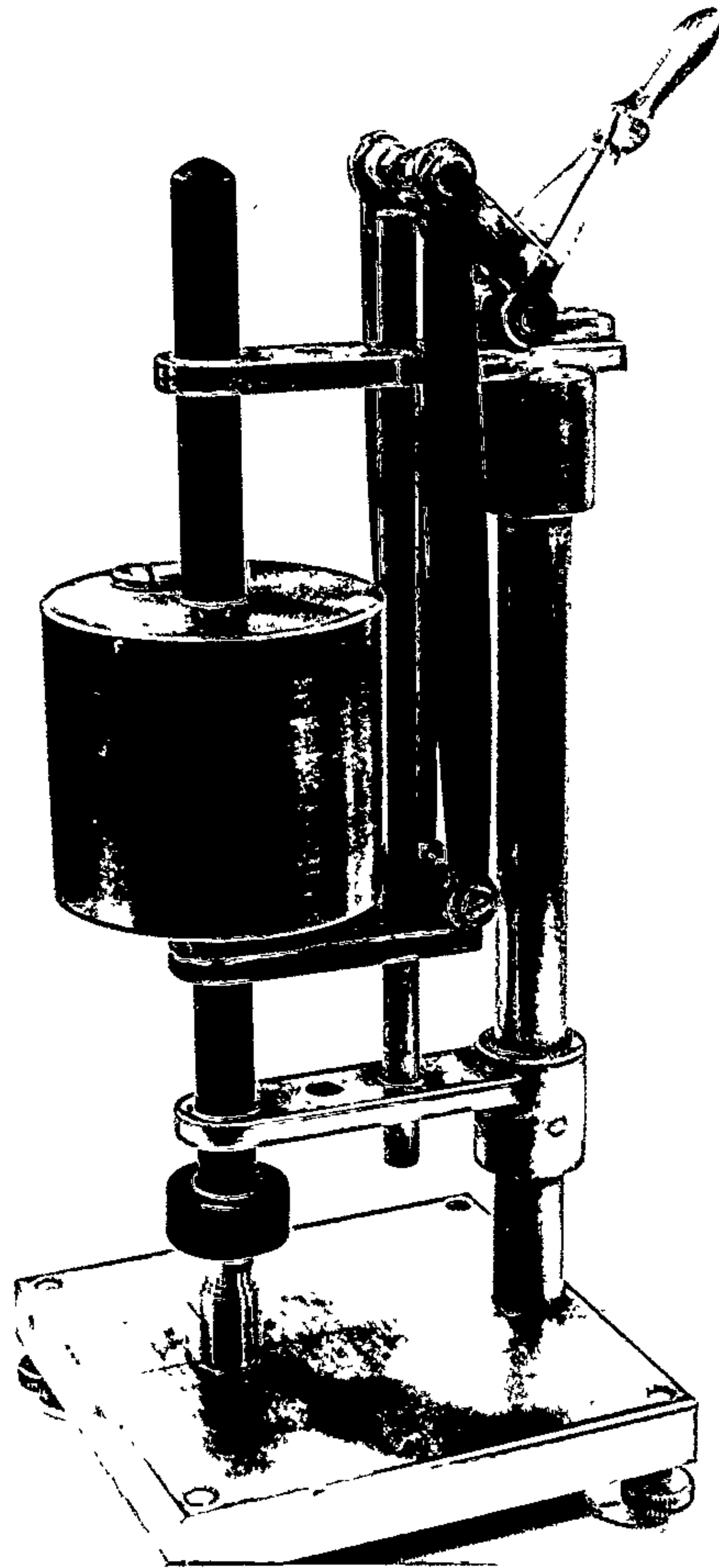


Figure 4.13

Casting seated on the die under an axial load of 2 Kg.

The measurements of the axial discrepancy were converted to diametral discrepancies by dividing by 10. This value was then expressed as a percentage of the gingival diameter of the die (9.8 mm), to give a measure of the accuracy of the casting.

$$\text{Casting accuracy} = \frac{x-y}{10} \times \frac{1}{9.8} \times 100 \text{ per cent}$$

#### 4.9 PROPERTIES OF THE LINING MATERIALS

In an attempt to explain the effect of these different ring lining materials on the fit of castings, it was considered desirable to study some relevant properties. These were their thickness, their water uptake and their effect on the W/P ratio of the investment mix in the casting ring.

##### 4.9.1 Measurement of Liner Thickness

Because of the easy compressibility of some of the materials, thickness measurements using a disc micrometer (designed for use on paper) gave equivocal results. So too did the use of a dial gauge comparator, even though it had a reduced spring force and an enlarged measuring foot. Therefore a modified bench comparator was constructed.

The instrument is shown in Figure 4.14. A comparator stand was fitted with the body of a linear variable differential transformer (Schawitz LVDT type DCD-050). The transducer core was attached to an aluminium shaft, which moved freely in nylon bushes and which was fitted with a ball anvil at its lower end. The total mass of shaft

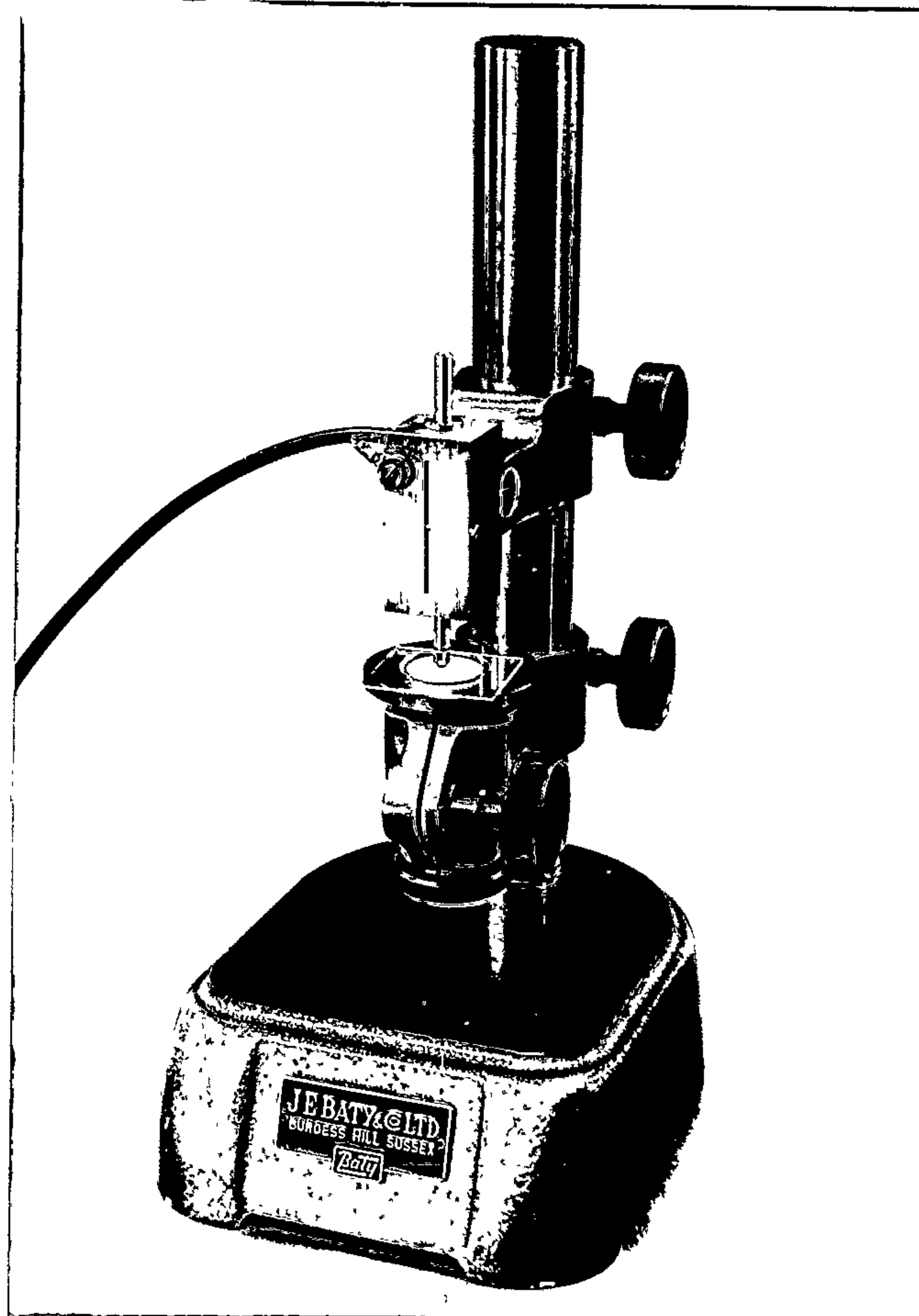


Figure 4.14

The modified bench comparator used for measuring the thickness of the liners.

and core was only 8 g. A 25 mm microscope cover slip distributed this measuring load over a specimen area of  $491 \text{ mm}^2$ . The output of the LVDT was adjusted by means of a potentiometer to give a calibration of  $1 \text{ mm} = 1 \text{ Volt DC}$ , and was read with a millivoltmeter.

The LVDT was zeroed with only the coverslip on the comparator table. Specimens of the various liners about 30 mm square in area were then inserted between coverslip and comparator table for thickness measurements.

Measurements were made on all liners both dry and wet. Absorbent liners (asbestos and cellulose) were wetted by immersion in water for 60 s and then drained until dripping of excess water ceased.

It was pointed out in Section 4.6 (p.113) that although the ceramic liners did not absorb water when immersed at atmospheric pressure, when they were used with vacuum investing they rapidly absorbed water from the investment mix under the influence of the applied vacuum. During setting of the investment they therefore functioned like any other wet liner, and as with the asbestos and cellulose liners it was considered necessary to measure their thickness when wet as well as when dry.

They were wetted by vacuum impregnation, in the following manner: specimens were immersed in water in a small vacuum chamber, and kept submerged with a superimposed piece of expanded metal mesh. The lid of the chamber was attached, and a vacuum of 720 mm Hg (96 KPa) was applied for 30 s, which was the same time interval as

was used in vacuum investing. Air was then admitted rapidly to effect water impregnation, and the specimens drained as before.

#### 4.9.2 The Water Uptake of the Liners

As already described in Section 4.5, casting rings fitted with the absorbent liners were weighed before and after wetting by the standardized technique, to determine their water content at the time of investing.

Since the ceramic liners, after vacuum investing, also functioned as wet liners, their water uptake under vacuum was determined. Impregnation in this case was done in the vacuum investing apparatus. Casting rings fitted with the various ceramic liners were weighed, and then attached to the 300 mL Vac-U-Spat normally used for investing patterns; in these experiments it simply contained water. In other respects the usual investing procedure was reproduced; a vacuum of 720 mm Hg (96 KPa) was applied by means of the Combination Unit, the Vac-U-Spat inverted so that the lined ring was filled with water, and the vacuum maintained for 30 s. The ring was then removed and drained, before reweighing.

#### 4.9.3 Effect of the Liner on the Effective W/P Ratio of the Mix

It has already been pointed out (Section 4.6, p.113) that when dry ceramic liners were used with vacuum investing, they absorbed water from the mix and reduced its W/P ratio; this produced an observable increase in the viscosity of the mix and a marked decrease in its manipulation time. It was also possible that the wet absorbent liners provided additional water to the unset mix, raising its effective W/P ratio. Such changes in W/P ratio occurring during

investing would alter both setting and thermal expansion of the investment mould.

Rate of setting is a sensitive indicator of changes in W/P ratio, and so was used to assess the effective W/P ratio of the investment mix in lined casting rings after vacuum investing. In the case of investments the end of the manipulation time occurs when the mix changes from a viscous liquid which will flow under vibration to a plastic solid which will not; it has been shown (Earnshaw and Marks, 1964) that this change is marked by the disappearance of the glossy surface from the mix. Therefore in these experiments time of loss of gloss was used as a parameter of rate of setting.

The same batch of Kerr Cristobalite Inlay investment was used, proportioned in the same W/P ratio of 0.40. Mixing was also performed as before: in a 300 mL Vac-U-Spat, at a speed of 425 r/min for 30 s. Casting rings, fitted with a sprue base and lined with wet asbestos, wet cellulose or dry ceramic materials, were filled in the same way as when patterns were being invested: vibrated under vacuum for 30 s.

After their removal from the Vac-U-Spat, the investment filled casting rings were placed under an illuminator which gave a collimated beam of light from an incandescent lamp; this produced a specular reflection of the lamp filament on the surface of the unset mix. The time when this specular reflection disappeared was recorded as the time of loss of gloss.

A series of control experiments was then made, using the same mixing procedure, with unlined casting rings, and with W/P ratios ranging from 0.28 to 0.48. Time of loss of gloss was determined as already described. The results so obtained were plotted to give a graph of time of loss of gloss against W/P ratio, and this graph allowed an estimate of the actual W/P ratios of the specimens produced by the filling of lined casting rings under vacuum.

## CHAPTER FIVE

### RESULTS

#### 5.1 DIMENSIONAL ACCURACY OF THE CASTINGS

The accuracy of the castings in a diametral direction, which was derived from the axial marginal discrepancy as described in Section 4.8 (p.116), is given in Tables 5.1 to 5.13. These results are combined and presented graphically in Figure 5.1.

#### 5.2 THICKNESS OF THE LINERS

The results of thickness measurements of the various lining materials, both dry and wet, are included in Tables 5.2 to 5.13 and are presented graphically in Figure 5.2.

For the tests on wet liners, the absorbent materials (asbestos and cellulose) were immersed in water at atmospheric pressure for 60 s, as was 2 mm Kaowool for one series of tests (K2NV in Figure 5.2). The ceramic liners were vacuum impregnated for 30 s. A second series of tests (K2) was made on 2 mm Kaowool under these conditions also.

#### 5.3 WATER UPTAKE OF THE LINERS

Values for the water uptake of the absorbent liners which were immersed at atmospheric pressure for 60 s, are also included in Tables 5.2 to 5.7.

The water uptake of the ceramic liners is included in Tables 5.8 to 5.12. The results given for the series of tests coded K2NV (Table 5.13) were obtained by immersion of the 2 mm Kaowool specimens under atmospheric pressure, and reproduced conditions when these liners were used without vacuum investing.

The results given in Tables 5.8 to 5.12 were obtained by immersing the specimens in water under a vacuum of 96 KPa, as described in Section 4.9.2 (p.119). This reproduced the conditions which were obtained when these liners were used with vacuum investing.

The water uptake of all the liners is presented graphically in Figure 5.3.

#### 5.4 EFFECT OF THE LINERS ON THE SETTING RATE OF THE INVESTMENT

For the reasons given in Section 4.9.3 (p.119), the time of loss of gloss was used as an indication of the end of the manipulation period of the investment.

The effect of different ring lining materials on this parameter of setting rate is given in Table 5.14 and is shown graphically in Figure 5.4.

## 5.5 EFFECT OF W/P RATIO ON SETTING RATE OF THE INVESTMENT

The results of measurements of time of loss of gloss at different W/P ratios are given in Table 5.15 and are shown graphically in Figure 5.5.

## 5.6 STATISTICAL ANALYSIS OF THE RESULTS

The means of the diametral discrepancies of the various groups of castings and the water uptake of the liners were compared using Student's  $t$  test. In most cases differences in mean fit, and in water uptake, between paired groups were statistically significant ( $P < 0.01$ ). The significance of the differences will be discussed.

The paired groups whose mean diametral discrepancies, and whose water uptake, were not significantly different are shown in Tables 5.16 (p.140) and 5.17 (p.141).

Table 5.1.

Discrepancy of control castings made with no ring liner.

| Code                          | Casting | Discrepancy<br>(%) |
|-------------------------------|---------|--------------------|
| C                             | 1       | - 0.64             |
|                               | 2       | - 0.65             |
|                               | 3       | - 0.59             |
|                               | 4       | - 0.59             |
|                               | 5       | - 0.68             |
|                               | 6       | - 0.66             |
|                               | 7       | - 0.55             |
|                               | 8       | - 0.63             |
|                               | 9       | - 0.57             |
|                               | 10      | - 0.50             |
|                               | 11      | - 0.60             |
| Mean $\pm$ Standard Deviation |         | - 0.61 $\pm$ 0.05  |

Table 5.2

Discrepancy of castings made with G.C. Asbestos Ribbon and the dry and wet thickness and water uptake of the liner.

| Code                      | Thickness<br>(mm) |      | Water<br>Uptake<br>(g)* | Casting | Discrepancy<br>(%) |
|---------------------------|-------------------|------|-------------------------|---------|--------------------|
|                           | dry               | wet* |                         |         |                    |
| GA                        | 0.86              | 1.07 | 2.08                    | 1       | + 0.04             |
|                           |                   |      | 2.03                    | 2       | - 0.02             |
|                           |                   |      | 2.36                    | 3       | - 0.11             |
|                           |                   |      | 2.48                    | 4       | - 0.08             |
|                           |                   |      | 2.24                    | 5       | + 0.06             |
|                           |                   |      | 2.30                    | 6       | - 0.20             |
|                           |                   |      | 1.88                    | 7       | - 0.10             |
|                           |                   |      | 2.13                    | 8       | - 0.11             |
|                           |                   |      | 1.81                    | 9       | - 0.07             |
|                           |                   |      | 1.82                    | 10      | - 0.19             |
|                           |                   |      | 2.20                    | 11      | - 0.27             |
| Mean ± Standard Deviation |                   |      | 2.12 ± 0.22             |         | - 0.10 ± 0.10      |

\* immersed 60s at atmospheric pressure.

Table 5.3

Discrepancy of castings made with Kerr Strip Asbestos and the dry and wet thickness and water uptake of the liner.

| Code                      | Thickness<br>(mm) |      | Water<br>Uptake<br>(g)* | Casting | Discrepancy<br>(%) |
|---------------------------|-------------------|------|-------------------------|---------|--------------------|
|                           | dry               | wet* |                         |         |                    |
| KA                        | 0.66              | 0.90 | 1.85                    | 1       | - 0.04             |
|                           |                   |      | 1.66                    | 2       | + 0.01             |
|                           |                   |      | 1.70                    | 3       | - 0.09             |
|                           |                   |      | 1.87                    | 4       | + 0.05             |
|                           |                   |      | 1.86                    | 5       | + 0.09             |
|                           |                   |      | 1.75                    | 6       | + 0.05             |
|                           |                   |      | 1.66                    | 7       | + 0.08             |
|                           |                   |      | 1.34                    | 8       | + 0.04             |
|                           |                   |      | 1.88                    | 9       | + 0.02             |
|                           |                   |      | 1.86                    | 10      | - 0.07             |
|                           |                   |      | 1.93                    | 11      | - 0.05             |
| Mean ± Standard Deviation |                   |      | 1.76 ± 0.17             |         | + 0.01 ± 0.06      |

\* immersed 60s at atmospheric pressure.

Table 5.4

Discrepancy of castings made with Shofu Asbestos Ribbon and the dry and wet thickness and water uptake of the liner.

| Code                      | Thickness<br>(mm) |      | Water<br>Uptake<br>(g)* | Casting       | Discrepancy<br>(%) |
|---------------------------|-------------------|------|-------------------------|---------------|--------------------|
|                           | dry               | wet* |                         |               |                    |
| SH                        | 0.45              | 0.48 | 1.23                    | 1             | - 0.36             |
|                           |                   |      | 1.15                    | 2             | - 0.37             |
|                           |                   |      | 1.54                    | 3             | - 0.39             |
|                           |                   |      | 1.39                    | 4             | - 0.34             |
|                           |                   |      | 1.31                    | 5             | - 0.40             |
|                           |                   |      | 1.06                    | 6             | - 0.37             |
|                           |                   |      | 1.74                    | 7             | - 0.39             |
|                           |                   |      | 1.00                    | 8             | - 0.28             |
|                           |                   |      | 1.32                    | 9             | - 0.32             |
|                           |                   |      | 1.06                    | 10            | - 0.40             |
|                           |                   |      | 0.94                    | 11            | - 0.27             |
|                           |                   |      | 1.31                    | 12            | - 0.32             |
| Mean ± Standard Deviation |                   |      | 1.25 ± 0.23             | - 0.35 ± 0.05 |                    |

\* immersed 60s at atmospheric pressure.

Table 5.5

Discrepancy of castings made with Austenal Ring Liner and the dry and wet thickness and water uptake of the liner.

| Code                      | Thickness<br>(mm) |      | Water<br>Uptake<br>(g)* | Casting | Discrepancy<br>(%) |
|---------------------------|-------------------|------|-------------------------|---------|--------------------|
|                           | dry               | wet* |                         |         |                    |
| AU                        | 0.40              | 0.55 | 1.97                    | 1       | - 0.23             |
|                           |                   |      | 2.03                    | 2       | - 0.34             |
|                           |                   |      | 1.84                    | 3       | - 0.29             |
|                           |                   |      | 1.89                    | 4       | - 0.45             |
|                           |                   |      | 1.55                    | 5       | - 0.29             |
|                           |                   |      | 1.98                    | 6       | - 0.25             |
|                           |                   |      | 2.13                    | 7       | - 0.25             |
|                           |                   |      | 2.16                    | 8       | - 0.17             |
|                           |                   |      | 1.96                    | 9       | - 0.19             |
|                           |                   |      | 2.08                    | 10      | - 0.18             |
| Mean ± Standard Deviation |                   |      | 1.96 ± 0.18             |         | - 0.26 ± 0.09      |

\* immersed 60s at atmospheric pressure.

Table 5.6

Discrepancy of castings made with Bego Mould inlay Strip and the dry and wet thickness and water uptake of the liner.

| Code                      | Thickness<br>(mm) |      | Water<br>Uptake<br>(g)* | Casting | Discrepancy<br>(%) |
|---------------------------|-------------------|------|-------------------------|---------|--------------------|
|                           | dry               | wet* |                         |         |                    |
| BE                        | 0.44              | 0.67 | 2.39                    | 1       | - 0.08             |
|                           |                   |      | 1.89                    | 2       | - 0.14             |
|                           |                   |      | 2.13                    | 3       | - 0.07             |
|                           |                   |      | 1.95                    | 4       | - 0.16             |
|                           |                   |      | 2.18                    | 5       | - 0.11             |
|                           |                   |      | 2.10                    | 6       | - 0.12             |
|                           |                   |      | 2.09                    | 7       | - 0.19             |
|                           |                   |      | 1.75                    | 8       | - 0.05             |
|                           |                   |      | 1.97                    | 9       | - 0.19             |
|                           |                   |      | 2.18                    | 10      | - 0.14             |
| Mean ± Standard Deviation |                   |      | 2.06 ± 0.18             |         | - 0.13 ± 0.05      |

\* immersed 60s at atmospheric pressure.

Table 5.7

Discrepancy of castings made with Whip-Mix Liner (Non-Asbestos) and the dry and wet thickness and water uptake of the liner.

| Code                      | Thickness<br>(mm) |      | Water<br>Uptake<br>(g)* | Casting | Discrepancy<br>(%) |
|---------------------------|-------------------|------|-------------------------|---------|--------------------|
|                           | dry               | wet* |                         |         |                    |
| WM                        | 0.74              | 0.93 | 1.95                    | 1       | - 0.41             |
|                           |                   |      | 2.06                    | 2       | - 0.39             |
|                           |                   |      | 1.84                    | 3       | - 0.25             |
|                           |                   |      | 2.07                    | 4       | - 0.32             |
|                           |                   |      | 2.21                    | 5       | - 0.23             |
|                           |                   |      | 2.06                    | 6       | - 0.58             |
|                           |                   |      | 2.10                    | 7       | - 0.28             |
|                           |                   |      | 2.11                    | 8       | - 0.58             |
|                           |                   |      | 2.13                    | 9       | - 0.44             |
|                           |                   |      | 2.29                    | 10      | - 0.28             |
|                           |                   |      | 2.19                    | 11      | - 0.34             |
| Mean ± Standard Deviation |                   |      | 2.09 ± 0.12             |         | - 0.37 ± 0.12      |

\* immersed 60s at atmospheric pressure.

Table 5.8

Discrepancy of castings made with Dentsply Kaoliner and the dry and wet thickness and water uptake of the liner. Because of the good reproducibility of the results only 5 measurements were made of water uptake.

| Code                      | Thickness<br>(mm) |      | Water<br>Uptake<br>(g)* | Casting | Discrepancy<br>(%) |
|---------------------------|-------------------|------|-------------------------|---------|--------------------|
|                           | dry               | wet* |                         |         |                    |
| DE                        | 1.34              | 1.27 |                         | 1       | - 0.20             |
|                           |                   |      |                         | 2       | - 0.14             |
|                           |                   |      | 3.56                    | 3       | - 0.15             |
|                           |                   |      | 3.50                    | 4       | - 0.11             |
|                           |                   |      | 3.63                    | 5       | - 0.24             |
|                           |                   |      | 3.53                    | 6       | - 0.14             |
|                           |                   |      | 3.59                    | 7       | - 0.13             |
|                           |                   |      |                         | 8       | - 0.11             |
|                           |                   |      |                         | 9       | - 0.26             |
|                           |                   |      |                         | 10      | - 0.15             |
| Mean ± Standard Deviation |                   |      | 3.56 ± 0.05             |         | - 0.16 ± 0.05      |

\* vacuum impregnated 30s.

Table 5.9

Discrepancy of castings made with G.C. Casting Liner and the dry and wet thickness and water uptake of the liner. Because of the good reproducibility of the results only 5 measurements were made of water uptake.

| Code                      | Thickness<br>(mm) |      | Water<br>Uptake<br>(g)* | Casting | Discrepancy<br>(%) |
|---------------------------|-------------------|------|-------------------------|---------|--------------------|
|                           | dry               | wet* |                         |         |                    |
| GC                        | 0.90              | 0.87 |                         | 1       | - 0.20             |
|                           |                   |      | 2.26                    | 2       | - 0.19             |
|                           |                   |      | 2.29                    | 3       | - 0.19             |
|                           |                   |      | 2.31                    | 4       | - 0.17             |
|                           |                   |      | 2.31                    | 5       | - 0.15             |
|                           |                   |      | 2.28                    | 6       | - 0.23             |
|                           |                   |      | 2.30                    | 7       | - 0.08             |
|                           |                   |      |                         | 8       | - 0.24             |
|                           |                   |      |                         | 9       | - 0.16             |
| Mean ± Standard Deviation |                   |      | 2.29 ± 0.02             |         | - 0.18 ± 0.05      |

\* vacuum impregnated 30s.

Table 5.10

Discrepancy of castings made with Kerr Flask Liner and the dry and wet thickness and water uptake of the liner. Because of the good reproducibility of the results only 5 measurements were made of water uptake.

| Code                      | Thickness<br>(mm) |      | Water<br>Uptake<br>(g)* | Casting | Discrepancy<br>(%) |
|---------------------------|-------------------|------|-------------------------|---------|--------------------|
|                           | dry               | wet* |                         |         |                    |
| KF                        | 0.83              | 0.88 |                         | 1       | - 0.23             |
|                           |                   |      |                         | 2       | - 0.24             |
|                           |                   |      | 2.18                    | 3       | - 0.19             |
|                           |                   |      | 2.05                    | 4       | - 0.21             |
|                           |                   |      | 2.15                    | 5       | - 0.21             |
|                           |                   |      | 2.34                    | 6       | - 0.21             |
|                           |                   |      | 2.05                    | 7       | - 0.09             |
|                           |                   |      |                         | 8       | - 0.24             |
|                           |                   |      |                         | 9       | - 0.29             |
| Mean ± Standard Deviation |                   |      | 2.15 ± 0.12             |         | - 0.21 ± 0.05      |

\* vacuum impregnated 30s.

Table 5.11

Discrepancy of castings made with 1 mm Triton Kaowool and the dry and wet thickness and water uptake of the liner. Because of good reproducibility of the results only 5 measurements were made of water uptake.

| Code                      | Thickness<br>(mm) |      | Water<br>Uptake<br>(g)* | Casting | Discrepancy<br>(%) |
|---------------------------|-------------------|------|-------------------------|---------|--------------------|
|                           | dry               | wet* |                         |         |                    |
| K1                        | 1.05              | 1.19 |                         | 1       | - 0.01             |
|                           |                   |      |                         | 2       | - 0.06             |
|                           |                   |      | 3.37                    | 3       | - 0.04             |
|                           |                   |      | 3.45                    | 4       | - 0.13             |
|                           |                   |      | 3.23                    | 5       | - 0.17             |
|                           |                   |      | 3.08                    | 6       | - 0.07             |
|                           |                   |      | 3.48                    | 7       | - 0.01             |
|                           |                   |      |                         | 8       | - 0.12             |
|                           |                   |      |                         | 9       | - 0.07             |
| Mean ± Standard Deviation |                   |      | 3.32 ± 0.17             |         | - 0.08 ± 0.06      |

\* vacuum impregnated 30s.

Table 5.12

Discrepancy of castings made with 2 mm Triton Kaowool and the dry and wet thickness and water uptake of the liner. Because of good reproducibility of the results only 5 measurements were made of water uptake.

| Code                      | Thickness<br>(mm) |      | Water<br>Uptake<br>(g)* | Casting       | Discrepancy<br>(%) |
|---------------------------|-------------------|------|-------------------------|---------------|--------------------|
|                           | dry               | wet* |                         |               |                    |
| K2                        | 2.64              | 2.54 |                         | 1             | + 0.04             |
|                           |                   |      |                         | 2             | - 0.04             |
|                           |                   |      | 5.37                    | 3             | - 0.01             |
|                           |                   |      | 5.86                    | 4             | + 0.16             |
|                           |                   |      | 5.48                    | 5             | - 0.02             |
|                           |                   |      | 5.79                    | 6             | + 0.15             |
|                           |                   |      | 6.04                    | 7             | - 0.02             |
|                           |                   |      |                         | 8             | + 0.05             |
|                           |                   |      |                         | 9             | + 0.11             |
| Mean ± Standard Deviation |                   |      | 5.71 ± 0.28             | + 0.05 ± 0.08 |                    |

\* vacuum impregnated 30s.

Table 5.13

Discrepancy of castings made with 2 mm Triton Kaowool, which were invested under atmospheric pressure, and the dry and wet thickness and water uptake of the liner. Because of good reproducibility of the results only 5 measurements were made of water uptake.

| Code                      | Thickness<br>(mm) |      | Water<br>Uptake<br>(g)*              | Casting | Discrepancy<br>(%) |
|---------------------------|-------------------|------|--------------------------------------|---------|--------------------|
|                           | dry               | wet* |                                      |         |                    |
| K2NV                      | 2.64              | 2.64 | 0.31<br>0.45<br>0.24<br>0.37<br>0.43 | 1       | - 0.11             |
|                           |                   |      |                                      | 2       | - 0.11             |
|                           |                   |      |                                      | 3       | - 0.17             |
|                           |                   |      |                                      | 4       | - 0.09             |
|                           |                   |      |                                      | 5       | - 0.19             |
|                           |                   |      |                                      | 6       | - 0.16             |
|                           |                   |      |                                      | 7       | - 0.15             |
|                           |                   |      |                                      | 8       | - 0.17             |
|                           |                   |      |                                      | 9       | - 0.26             |
|                           |                   |      |                                      | 10      | - 0.09             |
|                           |                   |      |                                      | 11      | - 0.19             |
|                           |                   |      |                                      | 12      | - 0.19             |
| Mean ± Standard Deviation |                   |      | 0.36 ± 0.09                          |         | - 0.16 ± 0.05      |

\* immersed 60s at atmospheric pressure.

Table 5.14

The effect of the liners on the time of loss of gloss of the investment.

| Type of Liner      | Code | No. of Tests Averaged | Time of Loss of Gloss (min)   |
|--------------------|------|-----------------------|-------------------------------|
|                    |      |                       | Mean $\pm$ Standard Deviation |
| Control (no liner) | C    | 3                     | 10.07 $\pm$ 0.12              |
| Asbestos           | GA   | 3                     | 9.87 $\pm$ 0.35               |
|                    | KA   | 3                     | 9.88 $\pm$ 0.23               |
|                    | SH   | 3                     | 10.83 $\pm$ 0.03              |
| Cellulose          | AU   | 3                     | 11.33 $\pm$ 0.03              |
|                    | BE   | 6                     | 10.95 $\pm$ 0.53              |
|                    | WM   | 3                     | 10.83 $\pm$ 0.18              |
| Ceramic            | DE   | 3                     | 1.60 $\pm$ 0.02               |
|                    | GC   | 6                     | 4.41 $\pm$ 0.45               |
|                    | KF   | 8                     | 6.68 $\pm$ 0.97               |
|                    | K1   | 6                     | 4.52 $\pm$ 0.55               |
|                    | K2   | 3                     | less than 1.33*               |
|                    | K2NV | 4                     | 9.75 $\pm$ 0.18               |

\* a result for K2 is not available because the mix lost its surface gloss and became plastic within the investing time of 1 min 20 s.

Table 5.15

The effect of the W/P ratio on the time of loss of gloss of the investment.

| W/P<br>Ratio | No. of Tests<br>Averaged | Time of Loss of Gloss<br>(min) |
|--------------|--------------------------|--------------------------------|
|              |                          | Mean $\pm$ Standard Deviation  |
| 0.28         | 3                        | less than 1.33*                |
| 0.30         | 3                        | 3.75 $\pm$ 0.15                |
| 0.32         | 3                        | 5.55 $\pm$ 0.20                |
| 0.34         | 3                        | 6.45 $\pm$ 0.28                |
| 0.36         | 3                        | 7.58 $\pm$ 0.47                |
| 0.38         | 3                        | 8.98 $\pm$ 0.07                |
| 0.40         | 3                        | 10.07 $\pm$ 0.12               |
| 0.42         | 3                        | 10.25 $\pm$ 0.17               |
| 0.44         | 3                        | 10.85 $\pm$ 0.02               |
| 0.46         | 3                        | 11.13 $\pm$ 0.12               |
| 0.48         | 3                        | 11.78 $\pm$ 0.08               |

\* a result at the W/P ratio of 0.28 is not available because the mix lost its surface gloss and became plastic within the investing time of 1 min 20 s.

Table 5.16

The following paired liners produced castings with discrepancies which were not significantly different at the confidence levels shown.

| Paired Liners |    |      | Confidence Levels (P value) |
|---------------|----|------|-----------------------------|
| GA            | vs | KA   | P > 0.05                    |
|               |    | BE   | P > 0.05                    |
|               |    | DE   | P > 0.05                    |
|               |    | GC   | 0.05 > P > 0.01             |
|               |    | K1   | P > 0.05                    |
|               |    | K2NV | P > 0.05                    |
| KA            | vs | K2   | P > 0.05                    |
| SH            | vs | WM   | P > 0.05                    |
| AU            | vs | WM   | 0.05 > P > 0.01             |
|               |    | GC   | 0.05 > P > 0.01             |
|               |    | KF   | P > 0.05                    |
| BE            | vs | DE   | P > 0.05                    |
|               |    | GC   | 0.05 > P > 0.01             |
|               |    | K1   | P > 0.05                    |
|               |    | K2NV | P > 0.05                    |
| DE            | vs | GC   | P > 0.05                    |
|               |    | KF   | 0.05 > P > 0.01             |
|               |    | K2NV | P > 0.05                    |
| GC            | vs | KF   | P > 0.05                    |
|               |    | K2NV | P > 0.05                    |
| KF            | vs | K2NV | 0.05 > P > 0.01             |

Table 5.17

The following paired liners gave values for water uptake which were not significantly different at the confidence levels shown.

| Paired Liners |    |    | Confidence Levels (P value) |
|---------------|----|----|-----------------------------|
| GA            | vs | AU | $P > 0.05$                  |
|               |    | BE | $P > 0.05$                  |
|               |    | WM | $P > 0.05$                  |
|               |    | GC | $P > 0.05$                  |
|               |    | KF | $P > 0.05$                  |
| KA            | vs | AU | $0.05 > P > 0.01$           |
| AU            | vs | BE | $P > 0.05$                  |
|               |    | WM | $P > 0.05$                  |
|               |    | KF | $P > 0.05$                  |
| BE            | vs | WM | $P > 0.05$                  |
|               |    | KF | $P > 0.05$                  |
| WM            | vs | KF | $P > 0.05$                  |
| DE            | vs | K1 | $0.05 > P > 0.01$           |
| GC            | vs | KF | $0.05 > P > 0.01$           |

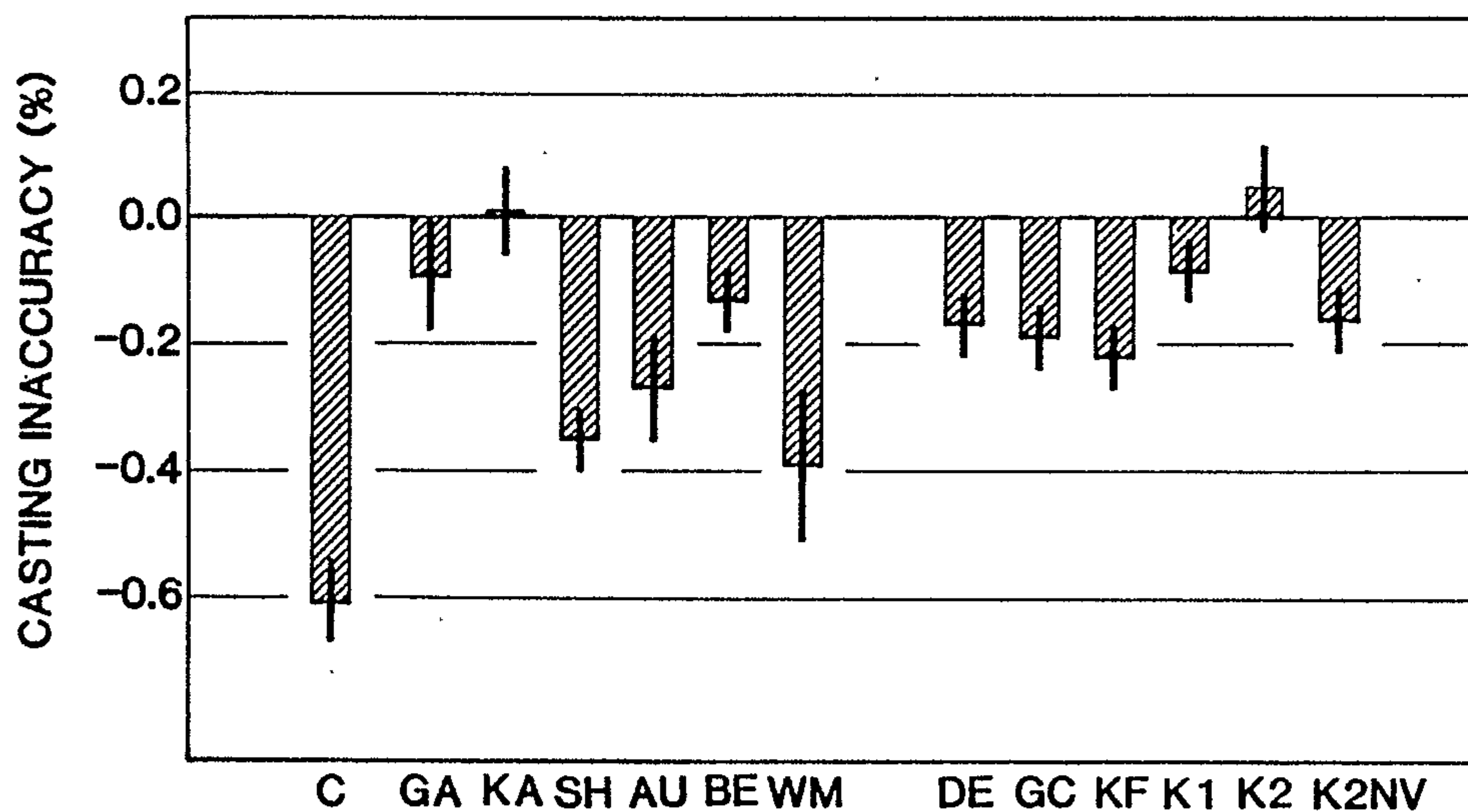


Figure 5.1

The effect of the liners on the casting inaccuracy (expressed as a diametral discrepancy) of the castings. Each bar represents the mean of at least 9 tests, and the small superimposed bars show the standard deviation in each case.

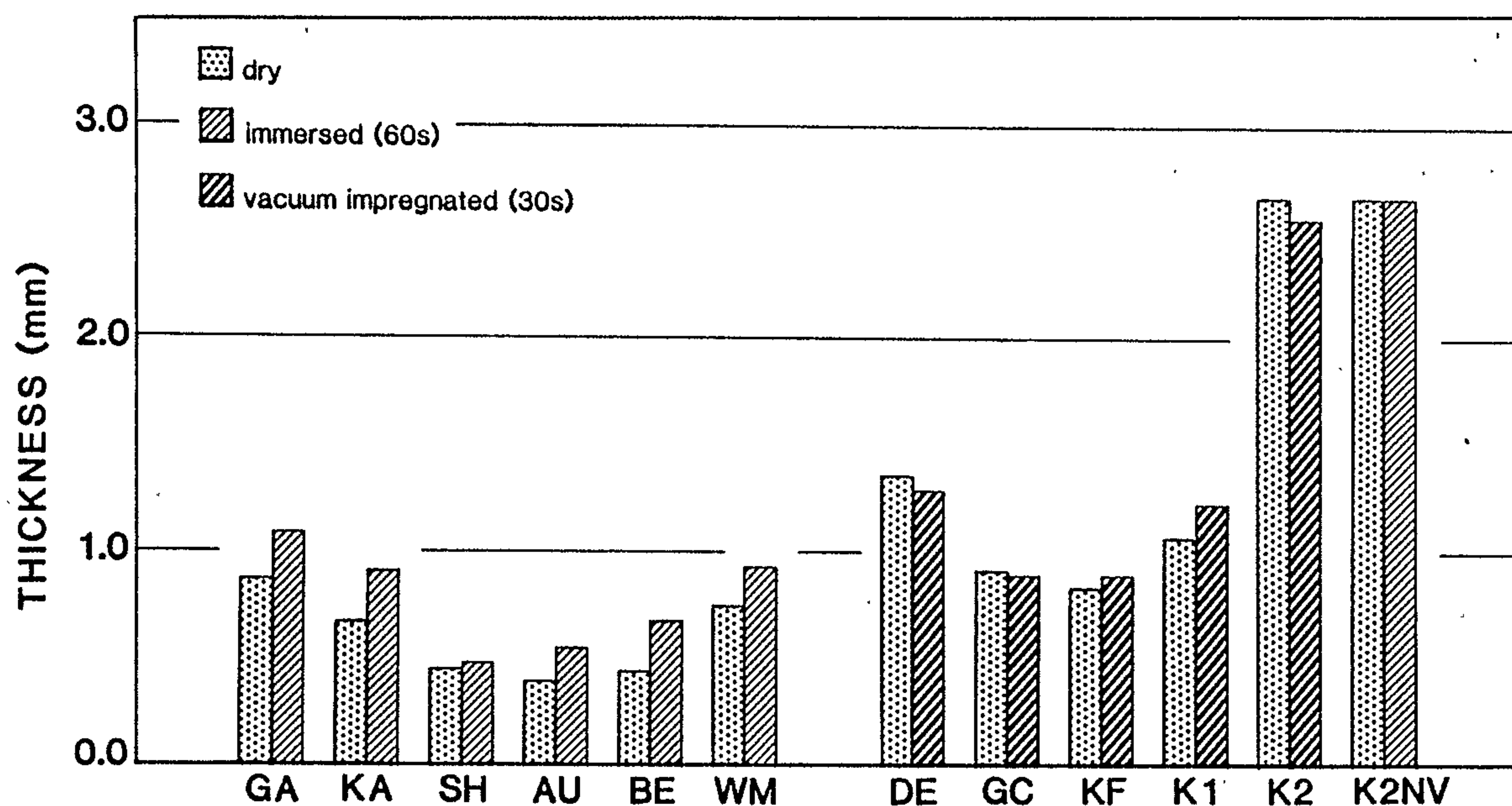


Figure 5.2

The thickness of the liners, tested dry and wet. The absorbent liners were immersed in water for 60 s before they were tested wet. The ceramic liners were vacuum impregnated for 30 s. K2NV was immersed for 60 s.

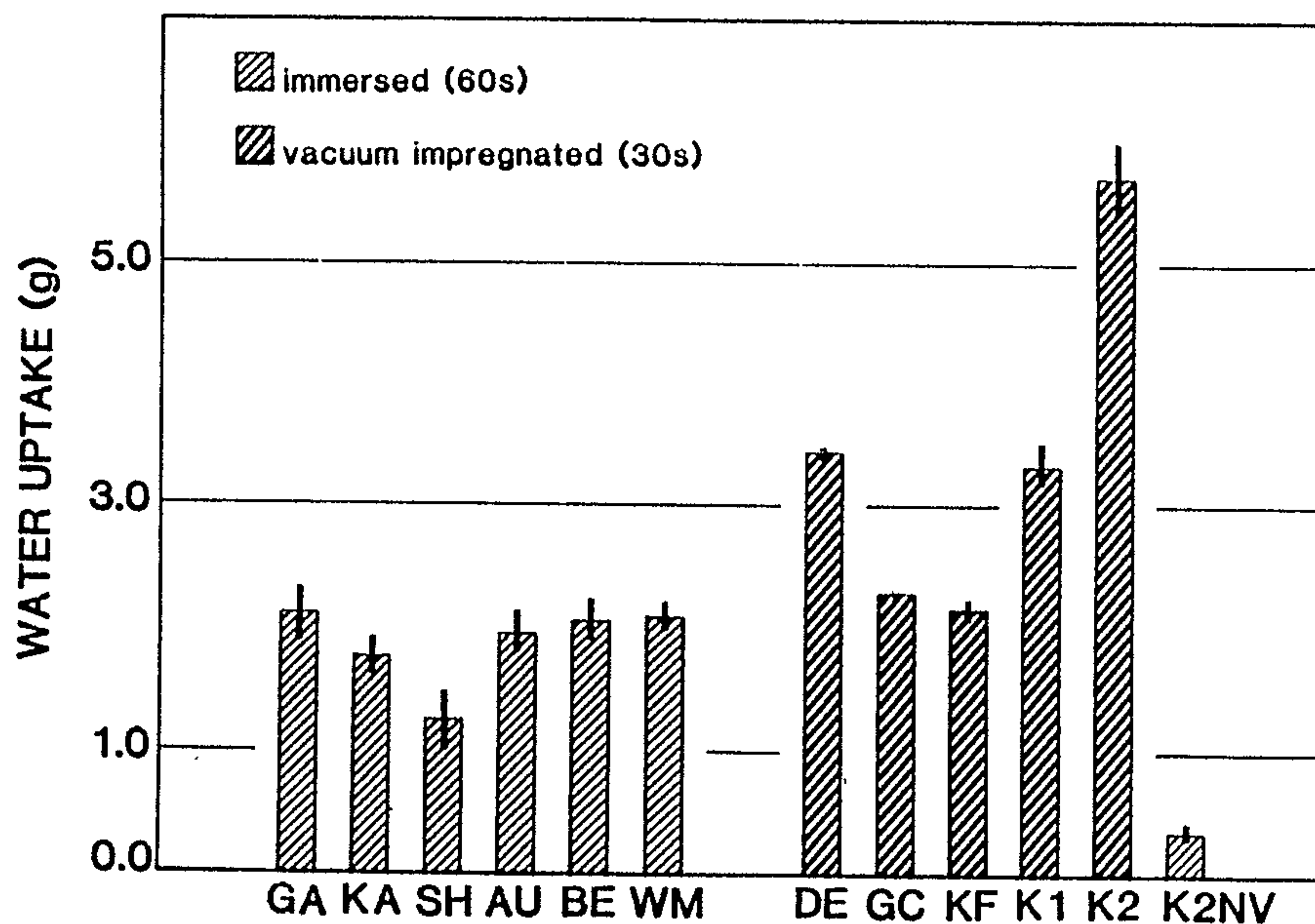


Figure 5.3

The water uptake of the liners. Each bar represents the mean of at least 5 tests, and the small superimposed bars show the standard deviation in each case. The absorbent liners were immersed in water for 60 s before they were tested. The ceramic liners were vacuum impregnated for 30 s. K2NV was immersed for 60 s.

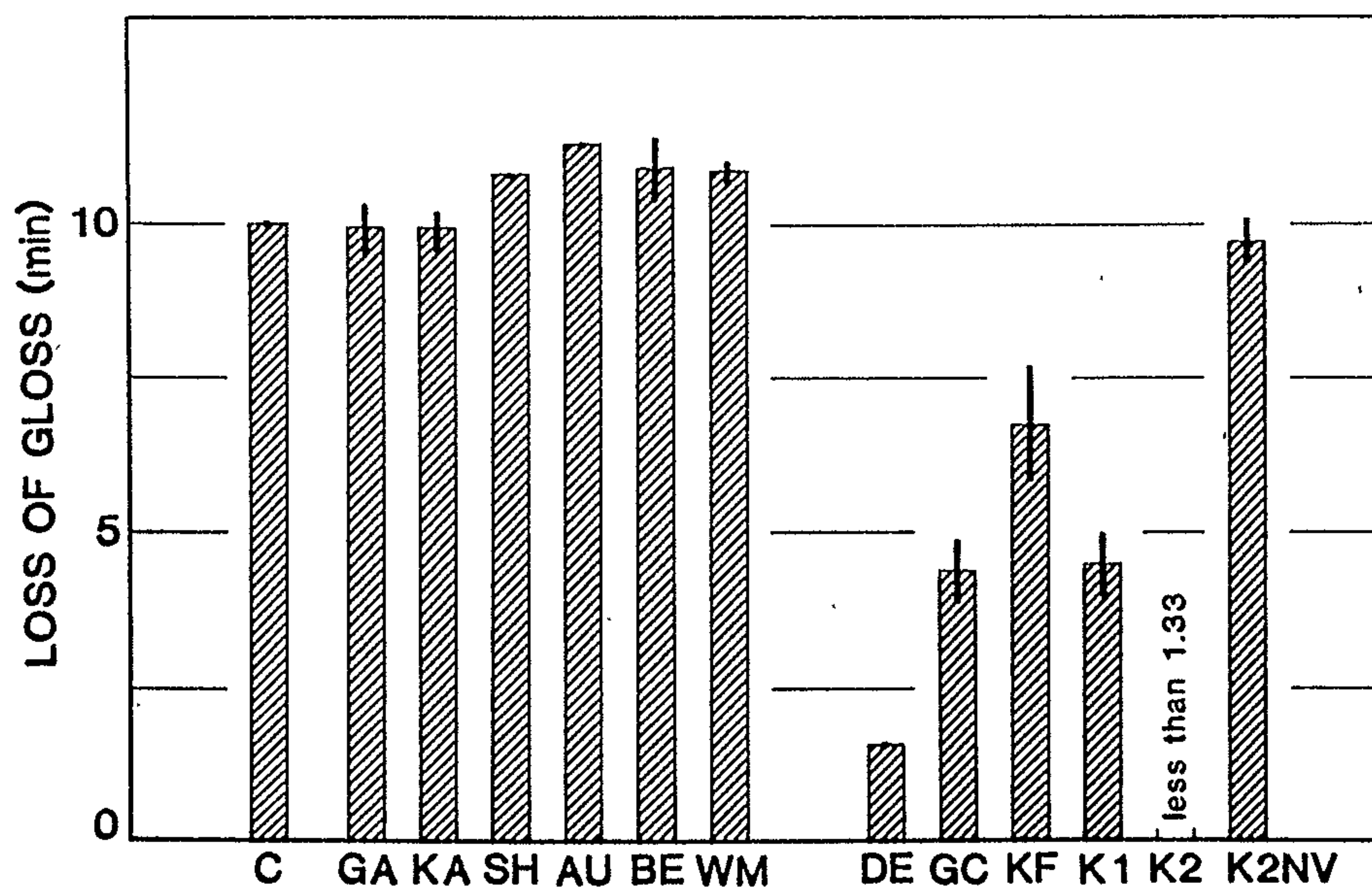


Figure 5.4

The effect of the various liners on the time of loss of gloss of the setting investment. Each bar represents the mean of at least 3 tests, and the small superimposed bars show the standard deviation in each case. A result for K2 is not available because the mix lost its surface gloss and became plastic within the investing time of 1 min 20 s.

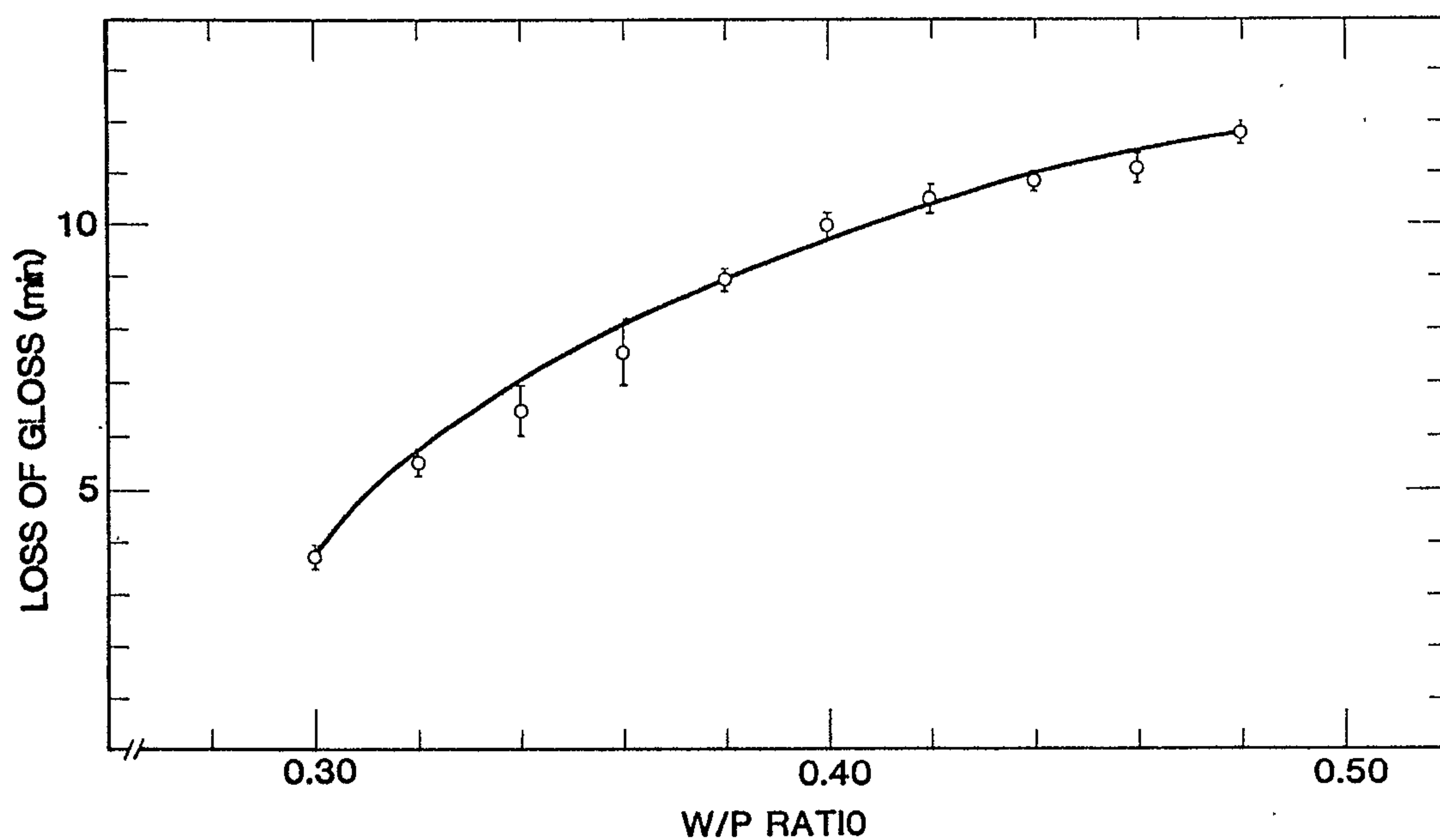


Figure 5.5

The effect of W/P ratio on the time of loss of gloss of the setting investment. The height of each vertical bar represents the standard deviation of the mean value in each case. A result at the W/P ratio of 0.28 is not available because the mix lost its surface gloss and became plastic within the investing time of 1 min 20 s.

## CHAPTER SIX

### DISCUSSION OF RESULTS

#### 6.1 INACCURACY OF CONTROL CASTINGS MADE IN UNLINED RINGS

Predictably, the control castings made in unlined rings gave the worst fit with a mean discrepancy of  $-0.61 \pm 0.05$  per cent (Table 5.1, p.125; Figure 5.1, p.142). The difference in the fit of these castings from the fit of all the other castings was highly significant ( $P < 0.001$ ).

Laboratory measurements (Earnshaw, 1985) showed that this batch of investment, setting under dry conditions, had a setting expansion of 0.4 per cent and a subsequent thermal expansion of 1.2 per cent, which gave a total expansion of 1.6 per cent.

When cooling from its solidus temperature to ambient temperature, the gold alloy would undergo an unrestricted thermal contraction in the range 1.7 to 1.8 per cent (Finger and Jørgensen, 1980), and this would represent its inherent casting shrinkage. However, the actual casting shrinkage would have been reduced to an unknown extent by the presence of the core of investment inside the solidified casting. The fact that these castings were on an average 0.61 per cent undersize indicates that somewhat less than 1.1 to 1.2 per cent investment expansion could have occurred in the unlined ring.

The ring would have completely prevented setting expansion of the investment in a lateral direction. It could be expected however

to allow a substantial amount of thermal expansion because the cartridge brass from which the ring is made has itself a high thermal expansion ( $\alpha_{(25 - 300^{\circ}\text{C})} = 19.9 \times 10^{-6}/\text{K}$ ). At the casting temperature used here ( $650^{\circ}\text{C}$ ) the ring had a linear thermal expansion of 1.25 per cent, which is in fact higher than that of the investment mould (Figure 6.1). However, it can be seen that in the temperature range  $250^{\circ}\text{C}$  to  $550^{\circ}\text{C}$  some restriction of investment expansion in a lateral direction would occur. Nevertheless, it would seem that, of the potential thermal expansion of the investment of 1.2 per cent, about 1.0 per cent did occur in a diametral direction in the unlined brass ring.

## 6.2 EFFECT OF THE LINERS ON CASTING ACCURACY

The mean diametral discrepancies of the castings made in casting rings lined with the various materials studied in this investigation ranged from + 0.05 per cent to - 0.37 per cent. Several workers have stated that a variation of  $\pm 0.2$  per cent in the absolute accuracy of a casting cannot be detected clinically (Scheu, 1933; Herbert and Thompson, 1934; Jørgensen, 1953; Suffert and Mahler, 1955). Therefore, if this is correct, there is a tolerance of  $\pm 0.2$  per cent within which the fit of a casting is acceptable under practical conditions. Based on this criterion, clinically acceptable castings could be made with this investment, in brass rings lined with G.C. Asbestos Ribbon and Kerr Strip Asbestos, Bego Mould inlay Strip and all the ceramic liners with the exception of Kerr Flask Liner (Figure 5.1, p.142). However, the considerable variation in the mean dimensional accuracy of castings made with the different liners can

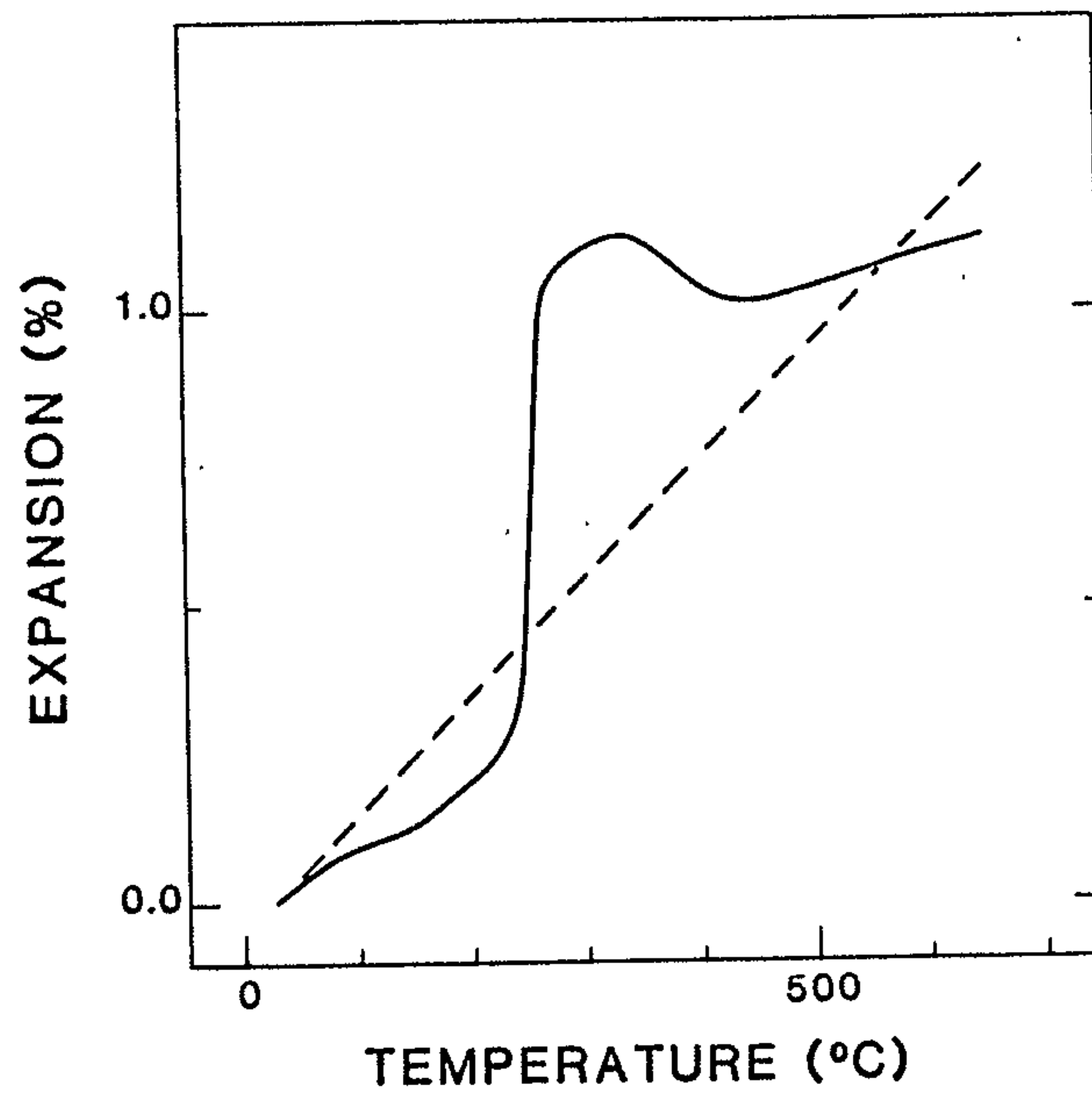


Figure 6.1

The thermal expansion of cartridge brass (70 per cent copper, 30 per cent zinc) and Kerr Cristobalite Inlay investment setting under dry conditions.

(courtesy of Dr R. Earnshaw)

only be discussed fully if the effect of the thickness and water content of the liners is also considered.

#### 6.2.1 The Absorbent Liners

Amongst the absorbent liners, all with the exception of Kerr Strip Asbestos produced predominantly undersized castings (Figure 5.1, p.142). The diametral discrepancy of castings made with Kerr Strip Asbestos was not significantly different from the fit of castings made with both G.C. Asbestos Ribbon ( $P > 0.05$ ) and Bego Mould inlay Strip ( $P > 0.05$ ). The thickness of these three lining materials when wet was also comparable (Figure 5.2, p.143) and they all absorbed more than 1.7 g of water when used as ring liners (Figure 5.3, p.144).

Shofu Asbestos Ribbon, Austenal Ring Liner and Whip-Mix Liner (Non-Asbestos) gave unacceptably undersized castings. Shofu Asbestos Ribbon was one of the thinnest liners and held the least water. However Austenal Ring Liner was similar to Bego Mould inlay Strip in thickness when dry and in its water content so that its inferior performance was surprising. A possible explanation is that the thickness of Austenal Ring Liner increased less when wetted compared with Bego Mould inlay Strip and by subjective assessment was considered to be a harder liner, therefore providing a less effective cushion in the ring. Even more surprising was the very poor fit of castings made with Whip-Mix Liner (Non-Asbestos), as both its thickness, dry and wet, and its water content were higher than those of Kerr Strip Asbestos. This liner was considered by subjective assessment to be one of the hardest tested.

Contrary to the findings of Yli-Urpo, Øilo and Syverud (1982) there was no evidence that the cellulose liners burned at the casting temperature (650°C).

A variable factor which was not studied quantitatively in this investigation was the relative softness of these liners, both dry and wet, and this may play an important part in their cushioning ability in the ring. The effective setting expansion of the investment which occurs in a lateral direction in lined casting rings depends both on the cushioning ability of the liners and on their water content. The added water they provide will enhance the observed setting expansion but the increased W/P ratio which results will also slightly decrease the thermal expansion of the investment (Earnshaw, 1982).

As already stated, castings made in unlined rings were on an average 0.61 per cent undersize. Under these conditions the setting expansion in a diametral direction would have been completely suppressed by the rigid casting ring. All the castings made in lined rings were less undersize. This clearly demonstrates that the presence of the liner, because of either its cushioning ability or the effect of the added water, or both of these factors combined, resulted in a greater overall expansion of the investment.

The ability of investments to expand when setting under applied stresses as great as  $800 \text{ g/cm}^2$  (Earnshaw, 1964) suggests that the wax patterns used in this study may not have entirely prevented the setting expansion of the investment core in the wax patterns. However, the effects of both the wax pattern and the ring liner on the effective setting expansion of the investment mould are variables

which are not fully understood and therefore require further investigation.

In contrast, it is known that the liner permits a more effective thermal expansion of the investment compared with that seen in unlined rings (Shell and Hollenback, 1965b; Shell, 1969).

However the fit of the castings made with the absorbent liners cannot be correlated with either the thickness of the liners, dry or wet, or their water content. This confirms the need for further studies of the effect of the softness of the liners, the effect of the added water in the liners on the true W/P ratio of the mix, and the effective setting expansion of the investment in the ring under these conditions.

#### 6.2.2 The Ceramic Liners

In the case of the ceramic liners, it is not only necessary to consider the effect of the thickness of the liners on the fit of the castings but, more importantly, the effect of vacuum investing. It has already been pointed out (Section 4.6, p.113) that when dry ceramic liners were used with vacuum investing they abstracted water from the mix. Gil, Moore and Dykema (1982) made a similar observation. This factor resulted in the dry liners, in effect, behaving in the same way as wet liners but in the presence of an investment mix with a reduced W/P ratio. The thicker mix would then have had an increased hygroscopic setting expansion and an increased thermal expansion.

Laboratory measurements (Earnshaw, 1985) of investment expansion, with ceramic liners which had been vacuum impregnated with water, gave values for setting expansion of about 1.2 per cent and a thermal expansion of 1.1 per cent, which gave a total expansion of 2.3 per cent. This value was identical to that obtained for investment expansion with wet Kerr Strip Asbestos (Earnshaw 1982). When Earnshaw used a dry ceramic liner, which had not been impregnated with water, the setting expansion was only 0.5 per cent, the thermal expansion was 1.1 per cent, which gave a total expansion of 1.6 per cent.

All the ceramic liners, when used with vacuum investing, reduced the W/P ratio of the mix and this effect was greater with the thicker liners. It should also be pointed out that three of the ceramic liners were thinner after vacuum impregnation (Figure 5.2, p.143).

Figure 5.3 (p.144) shows that the vacuum impregnated liners absorbed from 2.15 g to 5.71 g water. In all cases this was greater than the water uptake of the absorbent liners after immersion, which ranged from 1.25 g to 2.12 g water.

Probably because of these factors, the ceramic liners provided some interesting and unexpected results. With the exception of 2 mm Kaowool (K2) all the ceramic liners produced undersized castings. When 2 mm Kaowool was used without vacuum investing (K2NV) these castings were also undersize. However, the fit of all the castings were within, or very close to, the accepted tolerance of  $\pm 0.2$  per cent. Kerr Flask Liner (KF) produced the most undersized castings

with a mean discrepancy of - 0.21 per cent. This liner was the thinnest in this group and therefore provided the least effective cushion. As could be expected Kerr Flask Liner also abstracted the least water from the mix. The estimated W/P ratio of the mix after vacuum investing with this liner, calculated from the loss of gloss tests, was 0.34 (Table 6.1).

Liners cut from 2 mm Kaowool, and used without vacuum investing provided the most effective cushion. The total diametral thickness of the liner in the ring was 5.28 mm. Also in the absence of a vacuum, the W/P ratio remained unaltered and yet the castings were undersize (mean discrepancy - 0.16 per cent). Surprisingly the fit of these castings (K2NV) was not significantly different from that of castings made with Kerr Flask Liner ( $0.05 > P > 0.01$ ). More importantly, the results in the series K2NV indicate that it is not possible to make oversized castings with this investment setting under dry conditions, when used at the average recommended W/P ratio of 0.40.

In contrast, castings made with the same liner (K2), with vacuum investing, had a mean discrepancy of + 0.05 per cent. As the cushion was the same as in the series K2NV, these oversized castings reflected the greatly reduced W/P ratio (less than 0.28) and therefore the greatly increased thermal expansion of the investment core, and possibly the increased setting expansion resulting from a wet liner.

With the knowledge that the thickest ceramic liner, without vacuum investing produced undersized castings, it could be expected

Table 6.1

The effective W/P ratio of the investment mix in casting rings estimated from the time of loss of gloss.

| Type of<br>Liner | Code | Effective W/P Ratio<br>of Investment |
|------------------|------|--------------------------------------|
| No Liner         | C    | 0.40                                 |
| Asbestos         | GA   | 0.40                                 |
|                  | KA   | 0.40                                 |
|                  | SH   | 0.44                                 |
| Cellulose        | AU   | 0.47                                 |
|                  | BE   | 0.45                                 |
|                  | WM   | 0.44                                 |
| Ceramic          | DE   | 0.29                                 |
|                  | GC   | 0.31                                 |
|                  | KF   | 0.34                                 |
|                  | K1   | 0.31                                 |
|                  | K2   | less than 0.28*                      |
|                  | K2NV | 0.40                                 |

\* a result for K2 is not available because the mix lost its surface gloss and became plastic within the investing time of 1 min 20 s.

that the thinner ceramic liners, under the same conditions, would produce even less acceptable castings. Further tests are indicated with the thinner dental ceramic liners, without vacuum investing. Under these conditions, the enhanced setting expansion which accompanies the use of wet liners would be completely eliminated. Consequently the subsequent reduction in the overall expansion of the investment may need to be offset by the use of an investment capable of a greater thermal expansion.

### 6.3 EFFECT OF THE LINERS ON THE TIME OF LOSS OF GLOSS

In an attempt to estimate the actual W/P ratio in the lined rings, after vacuum investing, measurements were made of time of loss of gloss at different W/P ratios (Section 4.9.3, p.119; Figure 5.5, p.146). By comparing these results with the observed time of loss of gloss when vacuum investing was simulated (Figure 5.4), an estimate could be made of the final W/P ratio under practical conditions. These results are presented in Table 6.1.

#### 6.3.1 The Absorbent Liners

G.C. Asbestos Ribbon (GA) and Kerr Strip Asbestos (KA) did not alter the W/P ratio of the investment. These liners absorbed 2.12 g and 1.76 g of water respectively, after immersion for 60 s (Table 5.2, p.126 and Table 5.3, p.127). In contrast, the other four absorbent and prewetted liners (SH, AU, BE and WM) all lost water to the mix and so effectively increased its W/P ratio (Table 6.1). The effective W/P ratios in the casting ring were estimated to range from 0.44 to 0.47. It is possible that, in part at least, the

accompanying reduction in the thermal expansion of the investment may be the reason for the poorer fit of the subsequent castings. It is equally possible that; although the setting expansion would have been greater in these cases, it may have been restricted in the investment core by the wax patterns. Moreover these liners may not have provided an adequate cushion, as their wet thicknesses ranged from 0.48 to 0.93 mm. Again, these variables deserve further investigation.

### 6.3.2 The Ceramic Liners

It has already been pointed out (Section 6.2.2, p.152) that all the ceramic liners, when used with vacuum investing, decreased the W/P ratio of the investment. The effective W/P ratio, in these cases, ranged from 0.34 (Kerr Flask Liner) to less than 0.28 (2 mm Kaowool). Kerr Flask Liner was the thinnest liner in this group (0.83 mm dry thickness) and 2 mm Kaowool was the thickest (2.64 mm dry thickness), therefore these results are not surprising. As would be expected, when 2 mm Kaowool was used without vacuum investing, under atmospheric pressure (K2NV), the effective W/P ratio as shown by the rate of setting remained unaltered. It has already been pointed out (Section 6.2.2, p.152) that the decreased W/P ratio in these cases would have resulted in a greater thermal expansion of the investment core and this observation is supported by the acceptable fit of the subsequent castings (Figure 5.1, p.142).

Under practical conditions G.C. Casting Liner and 1 mm Kaowool had the same effect on the W/P ratio of the investment, which was reduced to 0.31. When tested dry, these liners were similar in thickness (GC, 0.90 mm; K1, 1.05 mm). However, they produced sets

of castings with a highly significant difference in mean dimensional inaccuracy. In the case of G.C. Casting Liner the mean inaccuracy was - 0.18 per cent, while with 1 mm Kaowool it was - 0.08 per cent ( $P < 0.005$ ). The better fit of castings made with 1 mm Kaowool may be related to its greater thickness (1.05 mm as against 0.90 mm, which represents a total difference of 0.30 mm in the casting ring).

Interestingly there is also a correlation of casting inaccuracy with the water uptake of these two liners after vacuum impregnation. Under these conditions the water absorption of G.C. Casting Liner was 2.29 g (Table 5.9, p.133), while that of 1 mm Kaowool, which gave castings with a much better fit, was 3.32 g (Table 5.11, p.135). However these latter measurements of water uptake, in which the liners were immersed in water under vacuum, do not closely reproduce practical conditions of vacuum investing.

In general these observations support the contention that when ceramic liners are used with a vacuum investing technique, they behave in the same way as absorbent and prewetted liners but in the presence of an investment with a reduced W/P ratio.

## CHAPTER SEVEN

### SUMMARY AND CONCLUSIONS

The effect of casting ring liners on the dimensional accuracy of full crown castings was examined in the hope of determining the acceptability of two types of lining materials introduced as alternatives to asbestos. These were based on cellulose and on ceramic wool. In addition the effect of vacuum investing on the water content of the liners and on the effective W/P ratio of the investment mix was examined to determine the effect of these variables on the fit of the castings.

Eleven materials were tested. These were:

- a) three asbestos liners,
- b) three cellulose liners,
- c) five ceramic liners.

All the asbestos and cellulose liners and three of the ceramic liners are commercially available dental products. Two of the ceramic liners (Kaowool 1 mm and 2 mm) are thermal insulating materials available for industrial use.

A series of control castings was made in unlined brass rings, and then castings were made in which all the liners were used with vacuum investing. The ceramic material Kaowool (2 mm) was also tested when invested under atmospheric pressure.

Annealed wax patterns and the subsequent castings, on their respective dies, were measured at their margins with a travelling microscope to determine the dimensional accuracy of the castings.

Some properties of the liners were also investigated. These were their thickness, their water uptake and their effect on the W/P ratio of the investment mix in the casting ring.

The following conclusions were drawn:

- a) The undersized castings made in unlined brass rings ( $- 0.61 \pm 0.05$  per cent) confirmed the need for casting ring liners.
- b) Provided the asbestos liners were thick enough, they produced castings which fell within the generally accepted range of tolerance of fit ( $\pm 0.2$  per cent) for clinically acceptable castings.
- c) The cellulose liners gave unpredictable results. The thickest cellulose liner, which absorbed the most water, produced the most undersized castings. Conversely the two thinner cellulose liners produced acceptable castings. Also these liners returned absorbed water to the investment mix and therefore substantially increased the W/P ratio of the mix. Such observations suggest that cellulose liners are not a suitable substitute for asbestos.
- d) All the ceramic liners, with the exception of Kerr Flask Liner, produced acceptable castings. However, when ceramic liners were used with vacuum investing, there was a marked decrease in the W/P ratio of the mix. Therefore when the ceramic liners were used with vacuum investing they behaved in the same way as absorbent and prewetted liners but in the presence of an investment with a reduced W/P ratio, and this thicker mix would

have had an increased setting expansion and an increased thermal expansion.

- e) Castings made with the thickest ceramic liner, without vacuum investing, were undersize ( $- 0.16 \pm 0.05$  per cent). It could be predicted that castings made with the thinner dental ceramic liners, without vacuum investing, would be unacceptably undersize.
- f) Based on the results shown in Figure 5.1 (p.142) ceramic liners can be recommended as the more suitable of the two replacements for asbestos if they are used with investing under atmospheric pressure and with an investment with a total effective expansion 0.1 to 0.2 per cent greater than that of the expansion of the investment used in this investigation.
- g) The results presented show that neither the thickness nor the water uptake of the liners show a direct correlation with the diametral fit of the castings. A better correlation may be found with the relative compressibility of the liners under load and it is proposed to extend this study to include this variable factor.

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