Mechanical Trituration.

Amalgams were prepared using an S.S. White and a Wig-l-bug amalgamator and their properties compared with hand mixed amalgams.

A time was determined for mechanical mixing which gave the same 1 hour compressive strength as the standard amalgam. These times are shown in Table 8.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Trituration Time (Seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mortar &amp; Pestle.</td>
</tr>
<tr>
<td>1.</td>
<td>40</td>
</tr>
<tr>
<td>2.</td>
<td>35</td>
</tr>
<tr>
<td>3.</td>
<td>45</td>
</tr>
<tr>
<td>4.</td>
<td>40</td>
</tr>
<tr>
<td>5.</td>
<td>45</td>
</tr>
<tr>
<td>6.</td>
<td>30</td>
</tr>
<tr>
<td>7.</td>
<td>45</td>
</tr>
</tbody>
</table>

In both mechanical amalgamators a pestle was used in the capsule to produce satisfactory mixing.

The S.S. White Amalgamator is a low energy amalgamator and as can be seen the mixing time is little reduced below that of a good mortar
and pestle.

The Wig-l-bug which is a high energy amalgamator considerably reduces the time of mixing.

The effects on the dimensional change of the different methods of mixing amalgam are shown in Figure 8.

It can be seen that there is little change in the dimensional change where the low energy amalgamator is used but where the high energy amalgamator is used there is a significant decrease in the expansion at 24 hours. Where specimens with comparable compressive strengths are prepared only alloys 5 and 6 produced a slight contraction, all other alloys maintaining a slight expansion.

Where there was additional trituration in the mechanical amalgamators, the compressive strength tended to follow a pattern similar to that of hand trituration but with a tendency to produce a contraction for all alloys.

It was observed that amalgams mixed in a high energy amalgamator exhibited a considerable rise in temperature during mixing. Temperature rises of up to 30° F. were measured. In a mortar and pestle and low energy amalgamator temperature rises of only 3 - 5° F. were observed.

Trituration Temperature.

Following the methods of Worner (1940) observations were made
on the effect of varying the temperature at which trituration is carried out.

Trituration was carried out at the standard time and under standard conditions at temperatures of 55°F, 72°F, 100°F, and 140°F.

The standard temperature at which trituration is carried out is between 70 - 75°F, so a temperature of 70°F may be regarded as the standard.

At temperatures below the standard, the 1 hour compressive strength was slightly but insignificantly reduced while at temperatures of 100°F and 140°F, the compressive strength was likewise slightly increased. It was observed however that at the higher temperatures, where the time of trituration was kept constant the result was slight over-trituration.

The effect on the dimensional change was as observed by Worner. Elevation of the temperature resulting in a slight decrease in the dimensional change at 24 hours while the lower trituration temperature produced a slight increase in the expansion at 24 hours.

Since the above changes could be attributed to overtrituration or undertrituration, the work was repeated, trituration being gauged by the state of the mix in the mortar. The results showed compressive strength values very closely related to the standard but the dimensional change values still varied from the standard by 1 - 2 microns/cm. (See Fig. 8).
It appears from this that the temperature of trituration may influence the dimensional change for the same amount of trituration.

**CONDESATION.**

While it is generally considered that an increase in the condensation pressure used causes an improvement in the physical properties of amalgam the true importance of all the factors involved in condensation is in general not clear.

The aims in condensing amalgam are:-

(i) Remove excess mercury.
(ii) Condense the particles together.
(iii) Remove the oxidised layer forming on particles.

The factors involved in the condensation of amalgam are:-

(i) force.
(ii) condenser size.
(iii) the number of thrusts on the condenser on each piece of amalgam.
(iv) the number of increments of amalgam.
(v) the size of the increments.
(vi) the time of condensation.
The effects of the various factors involved in the condensation of amalgam will be considered first as they affect compressive strength.

Using the standard 1.5 mm. plugger, the effect of varying the force of condensation was studied.

Forces of 3 pounds, 6 pounds, 10 pounds and 15 pounds were studied and the effect of increasing the force was to increase the compressive strength both at 1 hour and 7 days.

The increase in 1 hour compressive strength is linear till a force of 10 pounds is reached after which there is a flattening of the graph (Fig. 9).

Table 9 shows the effect of increasing the condensation force on the compressive strengths at 1 hour and 7 days.

While the effect on the 1 hour compressive strength was quite marked, the observed effect on the 24 hour compressive strength was relatively small, for changes in the condensation force. This is similar to the results obtained for changes in mercury:alloy ratio and trituration work.

Despite the use of a comparatively high condensation load it was not possible by varying the load to produce 1 hour compressive strengths
TABLE 9.

Compressive Strength (P.S.I.)

<table>
<thead>
<tr>
<th>Condensation Load (pounds).</th>
<th>1 Hour.</th>
<th>7 Day.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Alloy.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>9,200</td>
<td>12,300</td>
</tr>
<tr>
<td>2.</td>
<td>10,300</td>
<td>14,000</td>
</tr>
<tr>
<td>3.</td>
<td>8,900</td>
<td>12,000</td>
</tr>
<tr>
<td>4.</td>
<td>9,200</td>
<td>13,900</td>
</tr>
<tr>
<td>5.</td>
<td>8,500</td>
<td>11,900</td>
</tr>
<tr>
<td>6.</td>
<td>10,500</td>
<td>14,500</td>
</tr>
<tr>
<td>7.</td>
<td>8,600</td>
<td>12,000</td>
</tr>
</tbody>
</table>

comparable with those caused by even a slight amount of attrituration (90 seconds).

Condenser Size.

The effect of altering the size of condensers was investigated, condensers with diameters 0.5, 1.0, 1.5, 1.75, 2.0, 2.5 and 3.5 mm. being investigated.

The effects of an alteration in the size of the condenser on the 1 hour compressive strength are shown in Fig. 9(b). This is typical of all the alloys tested.

It is obvious that with a reduction in the size of the condenser
there is an increase in the 1 hour compressive strength. The effectiveness of increasing the pressure by reducing the size of the condenser is not as marked as an increase in pressure by an increase in the actual condensation force and in fact at higher condensation loads the smaller condensers become less effective than the larger ones. This is no doubt due to the condenser simply pushing through the amalgam without condensing it. Even at very low condensation loads, one has the feeling that the small (0.5 and 1.0 mm.) condensers are not as effective as the larger ones, although results prove otherwise.

A limited study of compressive strength values obtained with various sized condensers at different loads was carried out for mould cavities with diameters 3, 5 and 6 mm. (with appropriate heights). The greater effectiveness of a smaller condenser was observed in the 3 mm. cavity while the greater effectiveness of a slightly larger condenser was observed for the larger cavities. Figure 9(c) shows the results obtained for the 6 x 3 mm. cavity. One interesting observation made was that for no sized cavity were the 2.5 or 3.5 mm. condensers really effective in increasing the 1 hour compressive strengths of the amalgam.

It appears that there is some relationship between the size of the cavity and the size of the condenser used and at high condensation loads a condenser approximately one third of the diameter of the cavity is most effective and at lower loads the diameter of the condenser may be
approximately one quarter of the diameter of the cavity. Too small a condenser is not effective because it fails to condense by not wedging the amalgam against the walls of the cavity and a condenser which is too large simply sits on top of the amalgam and does not effectively condense it.

The Number of Thrusts on Each Increment.

The effect of altering the number of thrusts on each piece of amalgam placed in the cavity is shown in Figure 9(d). Eight increments were used and the number of thrusts varied from 5 to 60. There is a corresponding increase in the 1 hour compressive strength with the increase in the number of thrusts. More than 60 thrusts per piece were not considered, because of the very great increase in the time required to condense the specimen.

There is a marked increase in the compressive strength where the number of thrusts rose from 5 to 10 per piece and then there was a slight reduction in the increase with further increase in the number of thrusts.

The Number and Size of Increments Used.

Instead of packing the specimen in 8 pieces, specimens were packed in 1, 2, 4, 6, 8, and 16 pieces, the number of thrusts on each piece being 25.

As expected the 1 hour compressive strength increased with an increase in the number of pieces and it may be observed that the strength
Fig. 10

Machine - 8 Increments

Machine - One piece

Condensation Force (pds.)

(a) 25 Thrusts/Increment
(b) 200 Thrusts/Specimen

Compressive Strength (10^3 P.S.I.)

No. of Increments.

1 2 4 6 8 16

1 2 4 6 8 16

1 minute
2 minutes

3 minutes
5 minutes

50 100 200 300

50 100 200 300
obtained by using 16 pieces with 25 thrusts on each is comparable with the strength resulting from overtrituration (see Fig. 10(a)).

Where a small number of increments was used there was a very significant decrease in the one hour compressive strength.

To eliminate the influence of the total number of thrusts on the total specimen, specimens were packed using varying numbers of increments and the number of thrusts adjusted, so that the total number of thrusts on the specimen was 200 (8 x 25). The results obtained (Fig. 10(b)), showed that the size of the increments is of major importance in relationship to the compressive strength. Using 16 increments (12 1/2 thrusts each) the strength compared very closely with that of an amalgam triturated for 90 seconds. A specimen packed in one piece with 200 thrusts of 10 pounds was weaker than one packed in 8 pieces with 25 thrusts of 3 pounds.

The Time of Condensation.

A suggestion that the time of application of each thrust may be of importance was investigated by applying the condenser for periods of 0.5 seconds per thrust, 1 sec./thrust and 1.5 secs./thrust. This proved to be difficult to standardize but the results tend to indicate that as the load is applied for a longer period of thrust the compressive strength is increased. The standard time of packing resulted in thrusts of approximately 0.5 seconds duration. When the condenser was allowed to dwell on the amalgam the time required for condensation was naturally correspondingly increased.
The results for this variation in the time of condensation for alloys 1, 4 and 6 are given in Table 10.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Time of Thrusts,</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>1.</td>
<td>15,400</td>
</tr>
<tr>
<td>4.</td>
<td>16,500</td>
</tr>
<tr>
<td>6.</td>
<td>16,000</td>
</tr>
</tbody>
</table>

Alloys 1 and 4 are typical of a medium and fine grained alloy while alloy 6 was most influenced by an increase in the time of application of the condensation load.

The factor of delaying condensation and packing "aged" amalgam was considered.

After trituratation amalgam was allowed to remain undisturbed for periods up to 5 minutes. The specimen was then packed in the normal manner.

Although the time at the conclusion of condensation was approximately 10 minutes from the beginning of trituratation, the alteration in compressive strength both at 1 hour and at 7 days was insignificant. In some specimens
the strength was very slightly reduced and in others very slightly increased.

A very significant decrease in strength was observed, where mercury was removed from the whole mass either immediately after trituration or immediately after the 5 minute period had elapsed. In these cases the amalgam was crumbly and virtually unusable.

A technique of mixing fresh batches of amalgam as required failed to increase significantly the compressive strength of amalgam specimens.

Machine Condensation.

Specimens were prepared using a hydraulic machine capable of applying high loads to a piston which constituted a 4 mm. plugger.

Loads of 50, 100, 200, 300 pounds were applied which correspond to pressures of approximately 2,500, 5,000, 10,000 and 15,000 pounds per square inch.

Specimens were packed in 8 increments the load being applied for a half minute and one minute to attempt to parallel the time of application of the load in hand packing. Specimens were also packed in one piece the load being applied for periods of 3 minutes and 5 minutes.

The results obtained are shown in Fig. 10 (c) and (d).

These results indicate that although pressures are used which
are greatly in excess of those used by hand, the compressive strength resulting is considerably less. They also show the value of applying the load for an increased time. Although there is no real basis for comparison the compressive strength values of specimens packed in increments is higher than those of specimens packed in one piece.

Mechanical Condensation,

Specimens were packed using a Hollenback pneumatic condenser and two different vibrating type condensers (Kerr and Dentatus).

Using the Hollenback condenser with an intermediate notch setting for the handpiece and a technique similar to that of the hand technique it was found that the compressive strength values for both 1 hour and 7 days were essentially the same as for the hand technique using a 10 pound load and 8 increments.

In using the two types of vibrating type condensers a technique was first used as outlined in the instructions available with the Dentatus Instrument. The cavity being packed in 3 increments using a very light load (just sufficient to cause the instrument to vibrate). The rapid vibration caused a good deal of mercury to be brought to the surface and when this was removed, the upper layer of amalgam appeared to be well condensed.

The results obtained by this technique for 1 hour compressive
strength were far below those obtained by the standard hand technique and for all alloys were in the vicinity of 6,000 pounds per square inch. The values for the Kerr instrument were very slightly higher than those for the Dentatus.

When a technique more related to the hand technique was used and the cavity filled in 8 increments results more closely related to those of the hand technique were obtained.

Loads of 3, 6, 10 and 15 pounds were exerted on the condenser. The results are shown in Table 11. It must be noted that at loads of 6, 10 and 15 pounds the amount of amalgam normally used to fill the cavity (28:20) was not sufficient and at loads of 10 and 15 pounds 3 mixes this size were required. The vibrating condenser point at a high load, tends to force its way through the amalgam, spreading uncondensed amalgam up the sides of the cavity which is removed with the excess mercury.

It can be seen that although the mechanical condensers were effective in producing a higher 1 hour compressive strength value, than a corresponding hand condensation technique, at low condensation loads, the position is reversed at higher loads. The strength obtained with virtually pure vibration using a vibrating type condenser does not compare with a well packed hand specimen.
TABLE 11.

<table>
<thead>
<tr>
<th></th>
<th>Load</th>
<th>Kerr.</th>
<th>Dentatus.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Alloy 1.</strong></td>
<td>3</td>
<td>10,700</td>
<td>10,500</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>12,900</td>
<td>12,600</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>15,200</td>
<td>14,800</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>15,400</td>
<td>16,000</td>
</tr>
<tr>
<td><strong>Alloy 6.</strong></td>
<td>3</td>
<td>10,900</td>
<td>10,900</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>14,200</td>
<td>13,600</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>15,500</td>
<td>15,200</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>15,500</td>
<td>15,400</td>
</tr>
</tbody>
</table>

The strengths at 24 hours for hard and mechanically condensed amalgams were found to be almost identical.

The Effect of the Condensation on Dimensional Change.

When the degree of condensation is varied by varying the load it is found that as the condensation increases there is a corresponding decrease in the dimensional change at 24 hours until a limiting value is reached.

Table 12 shows the effect on dimensional change of increasing the force of condensation.
### TABLE 12.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Condensation Load (pounds)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td>1.</td>
<td>+12</td>
</tr>
<tr>
<td>2.</td>
<td>+13</td>
</tr>
<tr>
<td>3.</td>
<td>+15</td>
</tr>
<tr>
<td>4.</td>
<td>+15</td>
</tr>
<tr>
<td>5.</td>
<td>+9</td>
</tr>
<tr>
<td>6.</td>
<td>+16</td>
</tr>
<tr>
<td>7.</td>
<td>+14</td>
</tr>
</tbody>
</table>

It may be seen that with an increase in condensation load beyond 10 pounds there is little decrease in the dimensional change except for alloy 5 which proved to be extremely sensitive to manipulative variables from the point of view of dimensional change.

Figure 11 shows the dimensional change curve for alloy 1 at various condensation loads and it is obvious that the alteration in dimensional change is not due or related to the initial contraction since no initial contraction takes place for this alloy. It is to be noted that for alloy 5 there was a slightly increased initial contraction contributing to a reduced expansion at 24 hours. The increase in expansion for low condensation loads takes place rather as a slightly increased rate of expansion which is slightly more prolonged.
Where the condensation pressure was varied by a variation in the size of the condensing instrument results tended to show little variation in the dimensional change. Where very large condensers 2.5 mm., 3.5 mm. were used the dimensional change was comparable with that produced by very low condensation loads but where very small condensers were used the dimensional change was not reduced below that of amalgam produced by the 1.5 mm. condenser.

The slight influence, of altering the condensation load or condenser area, on the dimensional change is not unexpected since the effect on the compressive strength is also relatively small.

The dimensional change of specimens produced by altering the number of thrusts of the condenser on the amalgam, or the number of pieces of amalgam used was probably of more importance because of the ability to produce amalgams having setting rates and one hour compressive strengths, comparable with those of greatly overtriturated amalgams. I had expected that these "overcondensed" specimens would exhibit a markedly reduced expansion or a contraction since condensation is thought to be a continuation of trituration.

The results obtained, showed that the increase in strength produced by extra condensation was not accompanied by a contraction and in fact the dimensional change at 24 hours for all alloys except alloy 5 varied from the "standard" dimensional change by only 1 or 2 microns.
Table 13 shows the effect on the dimensional change of increasing the number of increments but keeping the number of thrusts for each increment at 25.

**TABLE 13.**

<table>
<thead>
<tr>
<th>Alloy</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>8</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>+18</td>
<td>+15</td>
<td>+10</td>
<td>+8</td>
<td>+7</td>
</tr>
<tr>
<td>2.</td>
<td>+17</td>
<td>+15</td>
<td>+9</td>
<td>+8</td>
<td>+8</td>
</tr>
<tr>
<td>3.</td>
<td>+20</td>
<td>+15</td>
<td>+14</td>
<td>+11</td>
<td>+11</td>
</tr>
<tr>
<td>4.</td>
<td>+20</td>
<td>+15</td>
<td>+12</td>
<td>+11</td>
<td>+10</td>
</tr>
<tr>
<td>5.</td>
<td>+16</td>
<td>+9</td>
<td>+5</td>
<td>+3</td>
<td>-1</td>
</tr>
<tr>
<td>6.</td>
<td>+18</td>
<td>+15</td>
<td>+11</td>
<td>+10</td>
<td>+11</td>
</tr>
<tr>
<td>7.</td>
<td>+20</td>
<td>+14</td>
<td>+12</td>
<td>+9</td>
<td>+8</td>
</tr>
</tbody>
</table>

Specimens packed in 1 or 2 pieces were slightly unsatisfactory because of very poor adaptation to the walls and angles of the die.

The effect on the dimensional change of all types of mechanical condensers employed was very slight. Specimens whether packed by hand or mechanically packed, and exhibiting comparable compressive strengths exhibited comparable dimensional changes. The influence of the vibrating type of condenser in conjunction with the higher condensation loads did
tend to very slightly decrease the dimensional change by a time
1 or 2 microns/cm. from that of hand packed specimens.

The Effect of Condensation on Flow.

Flow is inversely related to the amount of condensation. It
is found that for all alloys an increase in the condensation whether
effected by an increase in condensation load, a decrease in condenser
size, an increase on the number of thrusts on the amalgam or an increase
in the number of increments used with an associated decrease in the size
of the increments causes a decrease in the flow.

Figure 11 shows the effect of varying the condensation load
and the number of increments on the flow for alloys 2 and 6 which were
respectively the least and greatest alloys influenced in this regard.

CONTAMINATION.

Contamination of specimens was carried out by using a squeeze
cloth saturated in water, storing the amalgam in water immediately after
trituration and before condensation and pouring saliva into the die during
the packing of the amalgam.

A series of specimens for compressive strength was set up at
intervals of 3 days over a period of six months. These specimens were
all crushed within a period of three days so that there was a series of
contaminated specimens ranging in age from 6 months to 3 days.

Except for alloy 6 there was no marked difference in the compressive strengths of all of these specimens. Specimens of alloy 6 which were older than 3 months tended to exhibit compressive strength values approximately 10% lower than uncontaminated specimens of the same age.

Differences in compressive strength values for the other alloys had to be attributed to experimental technique being of the order of 5 - 6%. Some 6 month old contaminated specimens were stronger than non contaminated specimens.

The effect of moisture contamination on dimensional change, followed the classical picture but for all alloys except alloy 6 the delayed expansion did not become evident till approximately 20 days after condensation, and the dimensional change did not usually exceed some 50 microns per cm.

In alloy 6 the delayed expansion became evident usually about the sixth day after condensation and reached values as high as 150 microns/cm.

Alloy 7 did not exhibit this delayed expansion.

Investigations were carried out, contaminating specimens which were known to be "weaker" being condensed at a very low load (3 pounds) and
having a mercury to alloy ratio of 10:5. For all alloys this resulted in an earlier observation of delayed expansion and a significant increase in the expansion. For alloy 6 dimensional changes up to 200 microns were observed while other alloys had dimensional changes ranging from 100 microns/cm. (alloy 2) to 150 microns/cm. (alloy 4). There was no alteration in the compressive strength which could be attributed to the moisture contamination.

Moisture contamination had no effect at all on flow.

REINFORCEMENT.

The effect of embedding threaded stainless steel wire in amalgams, was observed. This wire (diameter 0.025") is used to secure additional retention, in badly "broken down" teeth, rather than provide additional strength for the amalgam, although the suggestion is frequently made that the wire has the effect of increasing the compressive strength.

Numbers of small pieces of wire ranging from 1 to 4 were placed into the amalgam in the die during condensation and the amalgam packed around them. It was found that these pieces of wire affected only the compressive strength of the specimen and have no influence on either flow or dimensional change.

The effect on compressive strength was to reduce both the strength at 1 hour and 7 days. The greater the number of pieces of wire used, the
greater the decrease in strength and where 4 pieces of wire were used this reduced the 1 hour strength to approximately one third of the normal strength and the 24 hour strength to approximately a half of the normal.

It was observed that in every case where wire was placed in a specimen, the faces of the fractured specimen contained the wire or its indentation.

TEMPERATURE.

Some observations were made on the effect of allowing amalgam to set at temperatures other than mouth temperature and while these have no clinical application, the results proved to be interesting.

Temperatures of $55^\circ F$, $72^\circ F$, $99^\circ F$, and $140^\circ F$ were observed for alloys 1, 5 and 6.

The results are shown on Figure 12.

It appears that amalgam has a temperature range at which setting is optimum and fortunately body temperature lies within this range. At temperatures of $55^\circ$ and $140^\circ$ the setting rate as measured by compressive strength is retarded. The eventual compressive strength is comparable at all temperatures. The retarding influence of the lower temperature is more pronounced than that of the higher temperature.

The influence of temperature changes on dimensional change is very slight there being no alteration in the initial contraction for any
Fig. 12
of the alloys tested but the secondary contraction at higher temperatures is slightly more marked. There is little actual change in the dimensional change at 24 hours, this being slightly less for higher temperatures than lower temperatures.

The effects of measuring flow at different temperatures were determined and it was observed that the flow was markedly increased as the temperature increased.

THE CUMULATIVE EFFECT OF VARIABLES.

As can be expected the effect of combining the manipulative variables results at times in an additive effect and at other times a partial cancelling out of the effects of the individual variables.

The possibilities for combining variables are almost limitless and all of these variables could not be investigated.

Figure 13 shows the effects of combining some of the manipulative variables.

In summary it may be said that where two variables are acting in the same direction on a physical property the effect of combining these may or may not be greater than the sum of the effects but acts in the same direction as the two variables.

The use of a very low condensation load combined with a high
Fig. 13.

<table>
<thead>
<tr>
<th>Hy. Alloy</th>
<th>9:5</th>
<th>9:5</th>
<th>9:5</th>
<th>8:5</th>
<th>7:5</th>
<th>5:5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trituration</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Condensation</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Increments</td>
<td>8.0</td>
<td>8.0</td>
<td>8.0</td>
<td>8.0</td>
<td>8.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Thrusts</td>
<td>25.0</td>
<td>50.0</td>
<td>50.0</td>
<td>25.0</td>
<td>25.0</td>
<td>25.0</td>
</tr>
</tbody>
</table>
initial mercury: alloy ratio results in an amalgam having a considerably lowered compressive strength and a considerably increased expansion as well as a markedly increased flow.

Where an amalgam is overtriturated and a low initial mercury: alloy ratio is used, the resultant amalgam specimen will have a compressive strength higher than that caused by either of these variables above but not as great as the sum of the increase in compressive strength.

Where two variables act in opposite directions, the combined effect is difficult to predict. Some examples of the combining of opposite variables which appear to apply constantly are:

(i) Where a variable tending to reduce expansion, e.g. overtrituration, is combined with a variable tending to increase expansion, e.g. a very low condensation load the effect on the dimensional change appears to be dominated by the variable causing the reduced expansion.

(ii) It is not usually possible to compensate for poor condensation by overtrituration, to produce desirable properties of compressive strength.

(iii) Very low condensation force cannot be rendered satisfactory even by greatly increasing the number of thrusts of the condenser but an improvement in condensation as measured by compressive strength may be gained by reducing the size of increments used.

It is not possible to make observations on the combined effects of all manipulative variables but the above examples serve to illustrate some principles which do seem to apply generally.
CHAPTER 4. THE MEASUREMENT OF DIMENSIONAL CHANGE.

During the early part of this investigation, when a satisfactory method of measuring dimensional change, with the equipment available, was being determined it was observed that the application of force to the specimen in the early stages of setting of the amalgam tended to decrease the expansion of the specimen under consideration, and in fact this may completely inhibit the expansion tendency of the amalgam.

When the anvil of the dial gauge used was placed on the specimen thereby exerting a force of 95 grams weight the specimen was found to show a rapid and considerable initial contraction and then remain unaltered in length.

Counterbalancing of the dial gauge to provide lower loads during measurement progressively reduced the initial contraction and allowed subsequent expansion to take place.

It was not until loads as low as 10 gm. were reached that a further reduction ceased to have any effect on the dimensional change.

Figure 14 shows the influence of the load during measuring of dimensional change for alloys 1 and 6.

Measurements without any load were made by lifting the spindle of the dial gauge a distance of 5 microns from the specimen and replacing
Alloy 1

Dimensional Change

Time (Hrs.)  4  8  12  16  20  24

0 gm.
5 gm.
25 gm.
50 gm.
95 gm.

Initial Reading at 15 min.

Fig 14.

Alloy 6

Dimensional Change

Time (Hrs.)  4  8  12  16  20  24

0 gm.
5 gm.
25 gm.
50 gm.
95 gm.

Initial Reading at 6 min.
it on the specimen only during readings. Lifting the spindle this short distance enabled the anvil to be consistently replaced without altering the reading. While this is not to be regarded as an ideal method of measuring dimensional change it served the purpose of the present observation. Desirably a very slight downward force should be exerted to enable constant contact to be maintained between the measuring instrument and the specimen, since alterations of 1 or more microns may be caused by irregularities in the specimen even where initial even contact between the instrument and the specimen is assured by a firm downward pressure.

Some points which I feel require consideration with regard to the measurement of dimensional change are:

(i) Dimensional change measurements may be a combination of true dimensional change and "low load, early" flow or compression of the amalgam.

(ii) Some alloys exhibit an initial contraction even when not subjected to an early low load while others do not exhibit this property until a high load is reached.

(iii) An interferometer because of the disposition of the support for the upper optical flat exerts a force approximately equal to half the weight of this optical flat on the specimen. The force exerted will be of the order of 25 gms. for a typical plate.
(iv) The influence of the force exerted on a specimen, on the early dimensional change will tend to be increased by:

(a) an early commencement of the measurement of dimensional change after condensation particularly where the specimen is packed in a mould of the exact dimensions of the final specimen without provision for removal of the mercury rich excess amalgam at the top of the specimen. A slowly setting uppermost layer may allow considerable settling of the anvil of a dial gauge or an interferometer plate.

(b) the use of a pointed or ball ended instrument for contacting the specimen which will settle into the amalgam with considerable facility.

(c) the use of a "pointed" specimen to support the measuring instrument or optical flat.

(d) measurements carried out at higher temperatures, since relaxation is greater with an increase in temperature. This may help to account for the increased initial contraction observed by some workers with a rise in the temperature of measurement of dimensional change.

It is necessary to maintain a very slight downward pressure on amalgam specimens during measurement. This however should be kept to a very low level by counterbalancing a dial gauge or the optical flat of an interferometer or using as thin an optical flat as possible on the interferometer. A broad contact should be maintained between the specimen and the measuring instrument.
CHAPTER 5. METALLOGRAPHIC PREPARATION.

The science of metallography has been defined (Kehl 1949) as the study of the structural characteristics or constitution of a metal or an alloy in relation to its physical and mechanical properties. From the microscopic examination of a prepared metal surface a good deal of information concerning the constitution of the metal or alloy may be obtained. Such things as grain size, the size, shape and distribution of phases and heterogeneous conditions may be observed. Since these may affect the physical properties, a study of them is valuable.

In order that a study of the microscopic structure of a metal or alloy may be of any value, it is essential that the surface of the metal be prepared so that it is truly representative of the metal under examination. A surface where disturbance of the structural elements has occurred has no value for microscopic examination.

In preparing the surface of the metal specimen we require:

(i) a good polishing technique which leaves the surface free from disturbed metal.

(ii) an etching technique which will show the structural constituents of the metal.

In carrying out a study of the microstructure of silver amalgam, my first aim was to satisfactorily polish the surface of the amalgam, find
an etchant which was suitable for the material and examine the characteristics of the microstructure for a standard specimen.

My second aim was to examine a series of specimens prepared by techniques containing various manipulative variables. The variables studied were basically the same as for the study of the physical properties already considered.

My third aim was to correlate my findings from the work on microstructure with the work on physical properties thereby making this a true metallographic investigation.

THE PREPARATION OF SPECIMENS.

The specimens used in this investigation were prepared in the standard die (8 mm. x 4 mm.) according to the standardized methods already outlined. Because of the need for the amalgam to have completely set to allow polishing to be properly carried out, the specimens were first used to determine the dimensional change for that particular technique. This proved valuable because, for every specimen examined, at least the dimensional change was accurately known. Because of the high degree of reproducibility of results for compressive strength and flow, I then felt that I was examining amalgam specimens with known physical properties.

Because of the time involved in the satisfactory preparation of specimens and the large number of specimens involved in the study (60),
many of the specimens were examined only in duplicate although some which appeared to be more important, and particularly in the early stages of the investigation when details of the structure and the influences of the variables on the structure was less well understood, were examined in triplicate.

MOUNTING.

Since specimens 8 mm. by 4 mm. could not be satisfactorily held for polishing it was necessary to mount them in some form of holder.

The technique of mounting had to be such that there would be very little rise in temperature which would cause removal of mercury from the specimen and alteration of its characteristics.

Two methods of mounting proved to be satisfactory.

(i) a full mount of epoxy resin was made by pouring the liquid resin around the specimen and allowing this to set over a 24 hour period at room temperature. This method produces a rise in temperature of less than 3°C.

(ii) a small hemi cylindrical hole was prepared in a piece of 1" lucite rod and into this is poured a small amount of self curing denture repair acrylic resin into which is placed the specimen. Because of the extremely small amount of resin used in this technique, the temperature rise of the specimen is less than 2°C.
Technique (ii) was the one used most frequently in this investigation. This offered the advantage of allowing examination of the specimen approximately 30 minutes after mounting.

The specimen is mounted in such a way that the long axis of the specimen lies parallel to the flat surface of a cylindrical mount.

PREPARATION OF SPECIMENS FOR MICROSCOPIC EXAMINATION.

(a) Polishing.

Because of the softness and high smear tendency of amalgam, metallographic polishing is one of the major problems involved in an examination of the structure of amalgam. When we add to the smear tendency the problem bringing mercury to the surface on overheating it can be seen that a very careful technique must be adopted and rigidly maintained.

Schmitt (1960) has suggested the use of a microtome to prepare a scratch free surface free of disturbed metal but a more standard metallographic technique is desirable if satisfactory.

The technique which I used is one using diminishing grades of abrasives as outlined by Samuels (1953).

(i) The specimen is first ground reasonably flat and until a sufficiently large area of specimen is available for examination. (A rectangular area approximately 8 mm. x 3 mm.). This is carried out
by grinding by hand on grades of Silicon Carbide papers 220, 400 and 600, on a flat glass bed and with a constant stream of water to prevent overheating. This leaves a considerable layer of disturbed metal which will be removed in subsequent operations.

(ii) The specimen is next ground with light hand pressure on an Alumina-Wax lap. This produces a specimen which is quite flat as the alumina particles are held firmly in the wax.

(iii) The specimen is next ground on a slowly revolving cloth covered wheel charged with diamond paste. Two grades of diamond paste are used, the first containing particles in the range 4 - 8 microns and the second particles in the 0 - 1 micron range. The diamond chips are suspended in a vehicle which is essentially stearic acid.

The use of diamond abrasive is probably the most important factor in the production of a surface which is completely free from deformity.

The diamond abrasive cuts very rapidly and consequently produces a surface which is not smeared during polishing. Because of this it is ideal for soft metals with a high tendency to deformation, including amalgam.

Care must be taken to keep the cloth well charged with the abrasive as a dry cloth will cease to cut and actually flow and burnish the surface of the specimen.
(iv) The specimen is finally polished by hand using "Heavy Magnesium Oxide" and water on a Selvyt cloth on a bronze polishing base.

The usual need exists for careful cleaning of the specimens between different abrasives.

After polishing and before etching the specimens were examined macroscopically and microscopically. The results of these examinations will be discussed in the relevant section.

(b) Etching.

The choice of a satisfactory etchant for silver amalgam has obviously been a major problem in the microscopic examination of amalgam. Little information of real value has been obtained from microscopic examinations of this material since frequently the etchants which have been considered to be satisfactory have left much to be desired. The problem may have been accentuated due to unsatisfactory techniques of polishing. Where the surface of the metal has been badly deformed during polishing the true value of an etchant can not be assessed because the structure has been revealed only at the expense of gross overetching. Where one phase has been completely removed by corrosive action an etchant must be regarded as having little value.

The problem of selecting an etchant is made more difficult because the exact action of this process is not known.
Etchants may function because of,

(i) the hydrogen ion concentration,

(ii) the hydroxyl ion concentration,

or (iii) the ability of the reagent to stain one or more of
the structural components preferentially.

The process is a preferential unbuilding of the polished
surface but whether the etching agent acts directly or as a catalyst
and whether the process is one of chemical corrosion or electrolytic
action is not known for certain. It is thought that with multiple phase
alloys the action is electrolytic. It therefore appears that the
selection of an etching agent is an empirical process.

The etchants investigated included:

(i) Acetic acid in various concentrations.

(ii) Hydrochloric acid in various concentrations.

(iii) 10% hydrochloric acid followed by 10% Ferric Chloride.

(iv) Sodium hydroxide in various concentrations.

(v) Ammonium hydroxide in various concentrations.

(vi) 30% nitric acid.

(vii) A double etch technique made up of a first solution
consisting of 8% Potassium Cyanide to which is added
1 gm. of Iodine per 25 ml. of solution. The second
solution consisted of equal parts of 10% ammonium
hydroxide and 10% potassium ferricyanide.
Etchants i, ii, iii, iv and v proved to be unsatisfactory. Solutions i, iv and v had little effect on the amalgam while solutions ii and iii tended to over etch. The use of HCl followed by FeCl₃ as advocated by Schmitt produced the same type of structures as developed by him. I considered this unsatisfactory because of the almost complete etching out of much of the amalgam.

Solutions vi and vii gave satisfactory results and the use of these was further investigated.

30% nitric acid completely etched the amalgam in 30 seconds giving the appearance shown in Fig. 38. The interpretation of this is discussed later. Longer etching with the nitric acid failed to develop a more detailed structure.

Technique vii proved to be very satisfactory also. The basic ingredients of this etchant have been used for the etching of amalgam alloys (Commonwealth Bureau of Dental Standards) and with modifications of the solutions to the percentages previously given and a modification of etching technique this proved to be the etch with perhaps the most potential but was most valuable when used in conjunction with the nitric acid etch as will be detailed later.

Simple immersion of the specimen in the solutions failed to produce a result. It was necessary to use the first solution on the polishing cloth with aluminium oxide or magnesium oxide in a polish
attack method. The specimen could then be immersed in the second solution to produce the basic appearance shown in Fig. 29 which will be discussed later. This technique was later modified and the first solution was applied to the specimen by swabbing lightly with cotton wool for 20 seconds. The specimen was then immersed in the second solution for 30 seconds. It is most important that the potassium cyanide, iodine solution is made up freshly daily.

THE EXAMINATION OF SPECIMENS.

As already mentioned both macroscopic and microscopic examination of the specimens was made.

The specimens were examined after polishing and before etching both by eye and by means of a metallurgical microscope at low magnification (20 X). Using a Bausch and Lomb metallograph the unetched specimens were examined at a magnification of 50 X and where indicated photographs were taken.

After etching, specimens were examined using the Bausch and Lomb Metallograph: magnifications of 250 X and 1000 X, and photographs taken for purposes of comparison.

The Bausch and Lomb instrument is ideal for this purpose being capable of excellent resolution.
CHAPTER 6. THE MICROSCOPIC EXAMINATION OF AMALGAM.

THE UNETCHED SPECIMEN.

A "standard" specimen was prepared for alloy 1 and polished as previously outlined.

When examined with the naked eye the specimen gave the impression of having a laminated appearance. There appeared to be 8 layers corresponding to the number of increments used in the packing of the specimen. (See Fig. 15).
When examined at a magnification of 50 it was obvious that the striations were formed by discrete holes. Figure 16 shows the appearance at a magnification of 50 of a section of the specimen. The area covered contains two bands of holes with a denser area between. The white areas are fully reflective and non-porous while the black areas represent the holes which are non-reflective. In the background may be seen pale grey areas which are the beginnings of the appearance of the structure of the amalgam. This is due to a very slight electrolytic etching effect which takes place during polishing on a bronze base, under the selvyt cloth.

![Figure 16. Alloy 1. Standard Specimen, unetched, 50 X.](image-url)
The presence of so much porosity was a surprise, in view of the fact that this was known to be a specimen prepared by a technique producing a high compressive strength both at 1 hour and 7 days. An examination of photomicrographs produced by other workers of etched amalgams revealed the presence of holes in all amalgam specimens illustrated.

It is interesting to note that the porosity was not evident until after the use of the diamond abrasives and at first I attributed the presence of the holes to the diamond. I discovered, however, that it was simple to produce a "hole free" polished surface by polishing without the use of the diamond. The surface was flowed and the holes burred over. The banding effect could then easily be reproduced using the diamond abrasive.

The aim of metallographic polishing is different from that of polishing clinical restorations. In the latter case the aim is to bur over any pits whereas in the former the aim is to produce a scratch free surface which has not been deformed during polishing. The diamond by cutting very rapidly "opens up" the surface rendering it porous.

The relationship of the porosity in the specimens to the technique of manipulation proved to be interesting.

(a) The Alloy Selected.

There was no difference in the disposition of the porosity...
for alloys 1, 3, 5 or 7 (the medium grain alloys). All showed the same layering effect for the standard technique of preparation.

The fine grained alloys likewise showed a similar picture to each other but different from the medium grained.

Although there was still a very slight tendency towards a layering effect (Fig. 17) the porosity was less than for the medium grained alloys and slightly less layered. This is in keeping with the increased facility of packing the fine grained alloys and also in keeping with the slightly increased compressive strengths of amalgams prepared from these alloys.

Fig. 17. Alloy 2. Standard Specimen, unetched, 50 X.
Fig. 18. Alloy 1. Mercury:Alloy 5:5, unetched, 50 X.

Fig. 19. Alloy 1. Mercury:Alloy 9:5, unetched, 50 X.
(b) The Mercury:Alloy Ratio.

The effect of altering the initial mercury:alloy ratio is shown in Figs. 18 and 19.

While the effect of decreasing the amount of mercury from the normal ratio has little effect on the porosity, the effect of increasing the ratio to 9:5 is to produce a good deal more porosity. The bands of holes are very much wider and the denser amalgam between is more porous. The increase in porosity may be due to the retention of additional mercury in the specimen or it may be due to the less effective condensation in the softer amalgam. The fact that Fig. 18 and Fig. 16 are similar despite more mercury in the specimen in Fig. 16 would tend to indicate a dependence on effectiveness of packing rather than mercury content. The increased porosity in Fig. 19 would tend to account for the lowered compressive strength of this specimen.

Figure 20 shows a specimen where mercury was added to maintain plasticity. There is a slightly different disposition of the porosity. The holes tend to be smaller, there is a reduced banding effect and the holes are distributed generally throughout the specimen.

(c) Trituration.

While the distribution of porosity in specimens which were undertriturated was essentially similar to the porosity in the standard specimen, the effect of overtrituration for both medium and fine grained
Fig. 20. Alloy 1. Replasticised, unetched, 50 X.

Fig. 21. Alloy 1, 180 secs. trituration, unetched, 50 X.
alloys was to produce the typical appearance shown in Fig. 21. Less banding is evident and there is a very general distribution of the very small holes in the specimen. The photomicrograph shown is for Alloy 1. This specimen would have a higher compressive strength than the standard specimen. The lowered porosity in this specimen is in keeping with the compressive strength increase. The similarity between Figs. 20 and 21 is interesting and it would appear that the addition of mercury to replasticize the mix of amalgam, with its attendant very slight amount of mulling necessary has the effect of increasing the trituration time for this specimen. This was also noticed with regard to the dimensional change of replasticized amalgams.

The effects of overtrituration were observed for fine grained alloys and were evident whether trituration was carried out by hand or mechanically.

(d) Condensation.

A study of the porosity caused by various condensation techniques proved to be most valuable and these photomicrographs gave a good deal of information concerning the condensation of amalgam.

The use of very low loads has a tendency to cause a very significant increase in porosity with a great increase in the width of the porous bands as can be seen in Fig. 22 which is from a specimen packed with a load of 3 pounds.
Fig. 22. Alloy 1, 3 pound condensation, unetched, 50 X.

Fig. 23. Alloy 1, Machine packed, unetched, 50 X.
The amount of porosity here compares with the porosity for an initial mercury:alloy ratio of 9:5.

That pressure per se is not the important factor in the condensation of amalgam may be seen from a study of Fig. 23 which is from a specimen packed by machine using a pressure of 10,000 pounds per square inch applied for 3 minutes. This specimen which was packed in one piece showed no banding but it did show a good deal of uniform porosity as may be seen in the photomicrograph. The fact that amalgam does not flow hydrostatically under pressure is well brought out here.

When a specimen was packed in one piece by hand, using 200 thrusts of 10 pounds each a most interesting result was obtained. Macroscopic examination revealed a small well packed semi circular area at the packed end of the specimen and the main body of the specimen appeared to be porous. Figure 24 shows photomicrographs of these two areas at the same magnification. This shows that using heavy hand pressure of 10 pounds the operator is able to condense amalgam for only a short distance and points to the need for the use of small pieces of amalgam.

Figure 25 helps to explain why the use of a mechanical condenser with a very low load (3 pounds) produces amalgam having a low compressive strength. The condenser apparently sits on the surface condensing a narrow surface layer well, but fails to penetrate into the mass of amalgam. At heavy loads the result obtained was similar to that for a well packed hand specimen.
Fig. 24. Alloy 1, packed one piece, 200 thrusts, unetched, 50 X.

The influence of the size of the increments used is borne out by a study of Figure 26 which was packed using 16 increments and an average number of thrusts of $12\frac{1}{2}$ per piece of amalgam. This specimen which would have an increased one hour compressive strength over that of the standard specimen and the porosity is distributed in narrower bands although there are twice as many of them. These bands were considerably reduced in width by an increase in the number of thrusts per piece with the greater number of pieces.

When a comparison is made between the porosity and the compressive strength of amalgam it appears that the porosity tends to reduce the
Fig. 25. Alloy I, Dentatus 3 pound load, unetched, 50 X.

Fig. 26. Alloy I, 16 Increments of 12 1/2 thrusts, unetched, 50 X.
compressive strength of the amalgam and has a greater influence on the strength at 1 hour than the strength at 24 hours. This is to be expected in view of the ability of the amalgam to bridge the holes when some strength has developed.

(e) Moisture Contamination.

In the light of the present knowledge concerning moisture contamination, I had expected that the presence of bubbles of hydrogen gas would be most obvious in specimens which had been allowed to age for some months after contaminated condensation. The results however were most surprising.

Immediately after polishing, the specimen gave an appearance similar to that of a normal specimen with no evidence of additional porosity. Within a few minutes of polishing however there appeared on the surface the configurations seen in Fig. 27. These proved to be very small bubbles on the surface of the amalgam which were approximately 1.5 microns high. On standing for approximately a further week there was evidence of large flat elevations on the polished surface. It appears that the gas collects in pockets but in very small cavities throughout the amalgam and after polishing a very thin layer of amalgam may be left overlying pockets of gas which can then expand causing surface bubbles. In view of the relatively slight influence on the 7 day compressive strength of a considerable increase in porosity (the difference in strength at 7 days of the amalgams in Figures 16 and 22 is approximately 10%) it is obvious
Fig. 27. Alloy 1, moisture contaminated, unetched, 50 X.

Fig. 28. Alloy 1, "Reinforced", unetched, 50 X.
why there was no significant decrease in strength for moisture contaminated specimens. There would tend to be a greater decrease where there were more cavities in which the hydrogen could collect and exert its influence on an already weakened amalgam.

(f) Reinforcement.

The effect of including a reinforcing wire in amalgam may be seen in Fig. 28.

The presence of a space beside the wire may be noticed and although the threads of the wire are still effective in providing retention, the presence of the space will tend to reduce the strength of the amalgam. Where a wire has been angled it may not be possible to adequately condense the amalgam around the wire which could give rise to greater space formation. (Fig. 28).
THE SPECIMEN AFTER ETCHING.

After etching specimens were examined at magnifications of 50 X, 250 X, and 1,000 X. A magnification of 50 X proved to be too low to be of any value in examining the etched specimens and beyond confirming that the disposition of the porosity was the same as before etching no further information could be gleaned at this magnification.

At a magnification of 250 X more information was available. The general picture was one of particles of the original alloy embedded in a matrix of what was undoubtedly the amalgam which had formed (Fig. 29).

Fig. 29. Alloy 1, Cyanide Etch, 250 X.
Information could be obtained at this magnification concerning the basic size and shape of the alloy particles, the presence of porosity, the relative proportions of original alloy and amalgam matrix, the wedging together of particles.

Figures 30 – 33 show examples of well condensed specimens all of which had a high compressive strength at 1 hour and 7 days while Figs. 34 – 37 show specimens having lower compressive strengths.

A study of Figs. 30 – 33 indicates that these amalgams have a large proportion of original particles and although these are closely packed together it is not certain that any wedging of the particles has occurred. Figures 30 – 33 are examples of amalgams formed by the standard technique, using a fine grained alloy, using a low mercury:alloy ratio and the use of 16 increments with 12½ thrusts per increment.

A comparison of Fig. 31 with the other Figs. 30, 32 and 33 fails to reveal a marked difference in the particle sizes of the original alloys although this specimen was prepared from a fine grained alloy.

A similar picture of good condensation is obtained with amalgams which have been subjected to additional trituration.

At this magnification there is little evidence of porosity in any one field. The porosity is shown in the areas which do not reflect light and consequently appear black in the photomicrograph.
Fig. 30. Alloy 1, standard, cyanide etch, 250 X.

Fig. 31. Alloy 2, standard, cyanide etch, 250 X.

Fig. 32. Alloy 1, Mercury:alloy 5:5, cyanide etch, 250 X.

Fig. 33. Alloy 1, 16 Increments, cyanide etch, 250 X.
Fig. 34. Alloy 1, 3 pound condensation, cyanide etch, 250 X.
Fig. 35. Alloy 1, Hg:alloy 9:5, cyanide etch, 250 X.

Fig. 36. Alloy 1, 20 secs. Trituration, cyanide etch, 250 X.
Fig. 37. Alloy 1, One piece pack, cyanide etch, 250 X.
Figs. 34, 35, 36 and 37 are examples of amalgams formed by using a low condensation load (3 pounds) an initial mercury:alloy ratio of 9:5, undertrituration and packing a specimen in one piece with 200 thrusts on the condenser.

A study of this group of photomicrographs shows an increase in the proportion of amalgam matrix and much less packing together of the original particles.

More porosity is evident in each specimen at this magnification.

Examination of the etched specimens proved to be very profitable at a magnification of 1,000 X.

The first etchant used to any extent was 30% HNO₃ as previously outlined and this gave a basic picture such as that shown in Fig. 38.

Fig. 38. Alloy 1, Hg:alloy 5:5, HNO₃ etch, 1500 X.
Since at this stage of this work I had little information concerning the structure of the amalgam, the interpretation which I placed on this picture was that the amalgam consists of a matrix of very pale grey material, which has a faint suggestion of being crystalline, in which are embedded some original alloy particles. The very large one in this photomicrograph being partially attacked by mercury while some of the small particles are completely attacked. There were some darker grey areas which are obviously not attacked at all and these are much more homogeneous than the original particles which have a stippled appearance. There is some evidence of porosity (dark spaces in this field). Having a knowledge of Schmitt's work I assumed that the dendriform structure was the $\gamma$ phase which had grown into the original particles and which is continuous with the matrix of amalgam. Why the mercury had not attacked the particles evenly and all the particles was a puzzle. I assumed that eventually all the particles may be completely attacked by mercury in the way that the small particles in Fig. 38 were. Although the nitric acid etch functioned very satisfactorily and easily and appeared to offer a good deal of information I was disappointed at the poor structure developed in the actual formed amalgam (matrix).

Following the development of a satisfactory technique for using the "cyanide" etchant the problem of lack of structure in the matrix was resolved and some further information obtained.

The typical appearance of an amalgam specimen etched by the "cyanide" etch is shown in Fig. 39.
Fig. 39. Alloy 1, standard specimen, cyanide etch, 1000 X.

This photomicrograph shows the crystalline structure of the amalgam matrix very clearly. Original particles of alloy may be seen embedded in the matrix and the presence of some porosity is evident. One surprising feature of this at first, was that the particles have apparently not been attacked by the mercury to any apparent extent, nor has the amalgam "grown" into the particles in keeping with the appearance shown in Fig. 38.

Since the cyanide etch seemed to be presenting a more truly representative picture of the amalgam, at this stage I decided to use it exclusively.

The examination of several specimens prepared by different
Fig. 40. Alloy 1, Hg:alloy 5:5, cyanide etch, 1000 X.

Fig. 41. Alloy 1, Hg:alloy 5:5, cyanide etch, 1000 X.
techniques revealed the presence of dark lines crossing some of the original alloy particles. Figs. 40 - 41.

At first I concluded that these were scratches but as they were multidirectional within very small fields further investigation was made. Examination by means of polarized light revealed the presence of twins so it was concluded that these lines were deformation lines or slip planes.

It is interesting to note in Fig. 40 the relationship existing between the lines of the slip bands in the large particle to the apparent eroding of the surface of the particle by the amalgam.

Different degrees of slipping has obviously occurred and the fine slip lines may give way to actual deformation lines or cracks and eventually the particles may fracture along these planes.

Since such lines should be associated with stressing of the particles, some original alloy was examined after normal metallographic preparation and etching, using the cyanide etch (Fig. 42). It may be seen that although some particles appear to be about to separate, there is no real evidence of deformation lines. An examination of Figure 42 also shows the presence of a second phase in some of the alloy particles although the particles are very homogeneous.
Fig. 42. Alloy 1, Original particles, cyanide etch, 1000 X.

That these deformation lines are not introduced during manufacture becomes evident when it is realised that although they are present to some degree in all specimens, there are specimens prepared by some techniques which are almost free of deformation lines.

Consideration will now be given to the effects of various manipulative variables on the structure of amalgams prepared from alloys 1 and 2 as evidenced in cyanide etched specimens.

The picture of a standard prepared specimen for alloy 1 was shown in Fig. 39 and this has already been described. The presence of some deformation lines may be seen in this photomicrograph as may the
lack of complete homogeneity in some particles.

The effect of varying the initial mercury:alloy ratio is shown in Figs. 40 and 43. Figure 40 for a specimen with an initial mercury:alloy ratio of 5:5 shows considerable evidence of deformation having occurred while Figure 43 prepared using a 9:5 ratio shows very little evidence of deformation. While little can be said of the grain size in the various specimens it may be seen that in Figure 43 there is more evidence of surface attack on the particles and the ingrowth of amalgam in Figure 43 than Figure 40. The difference in the degree of deformation in these specimens may be due to the longer amount of dry grinding during triturating with the low mercury:alloy ratio and the lubricant action of the excess mercury in the high mercury:alloy specimen.

Fig. 43. Alloy 1, Hg:alloy 9:5, cyanide etch, 1000 X.
Fig. 44. Alloy 1, 180 secs. Trituration, cyanide etch, 1000 X.

Fig. 45. Alloy 1, 20 secs. Trituration, cyanide etch, 1000 X.
The effects of trituration are shown in Figs. 44 and 45 which show an overtitrated specimen and an undertiritated one. There is considerably more evidence of deformation in the overtitrated specimen than the undertiritated one.

In Figure 46 is shown a specimen prepared by slight overtitruration using a Wig-1-bug. Apparently the very vigorous action of the Wig-1-bug causes considerable deformation of the alloy particles without necessarily a breaking up of these particles.

When the temperature of trituration was varied it was found that there is a slight increase in the amount of deformation occurring at the higher temperature (Figs. 47, 48).
Fig. 47. Alloy 1, Triturated 55°F., cyanide etch, 1000 X.

Fig. 48. Alloy 1, Triturated 140°F., cyanide etch, 1000 X.
The effect of varying the amount of condensation has little apparent effect on the structure at this magnification. Figures 49 and 50 show the structure of specimens packed using a 3 pound load and 16 increments with 25 thrusts of 10 pounds respectively.

Although the undercondensed specimen has more amalgam matrix and less particles and several large areas of porosity the degree of deformation for both of these specimens is comparable.

In Figs. 51, 52 are seen photomicrographs of amalgams prepared from alloy 2 (a fine grained alloy) for the standard technique and over-trituration. This alloy behaves in exactly the same way as alloy 1 and in fact at this magnification the structure of various amalgams prepared from alloy 2 cannot be distinguished from those of alloy 1, these behaving in an exactly similar manner for all the manipulative variables considered and the final amalgams having particles of comparable size although occasional larger particles were visible in amalgams prepared from the larger grained alloy.

Figure 53 shows the appearance of an amalgam which was contaminated by moisture in the manner described earlier, while Figures 54 and 55 show the appearances of amalgams kept plastic by the addition of mercury after trituration and where packing was delayed for 5 minutes after trituration.
Fig. 49. Alloy 1, 3 pound condensation, cyanide etch, 1000 X.

Fig. 50. Alloy 1, 16 Increments, cyanide etch, 1000 X.
Fig. 51. Alloy 2, standard, cyanide etch, 1000 X.

Fig. 52. Alloy 2, 180 secs. Trituration, cyanide etch, 1000 X.
Fig. 53. Alloy 1, Moisture contaminated, cyanide etch, 1000 X.

There is little discernible difference between these amalgams and those prepared by the standard technique, although there are slightly more stress lines in the replasticised amalgam than the standard.

An examination of amalgams which had been allowed to set at different temperatures revealed no difference in the microscopic structure as observed following this technique.

A consideration of the preceding series of photomicrographs reveals that there is little difference in the size of the crystals in different amalgam specimens and the shape of these crystals varies considerably within each specimen which is due to the cutting of crystals in different planes.
Fig. 54. Alloy I, Replasticized, cyanide etch, 1000 X.

Fig. 55. Alloy I, Delayed packing, cyanide etch, 1000 X.
The stress lines in the original alloy particles appear to be associated with additional trituration or a reduction in the initial ratio of mercury to alloy. Stress lines were found to be present in both fine and medium grained alloy particles. The marked reduction in the number of stress lines present is particularly evident in amalgams prepared using a high initial mercury:alloy ratio, and where the amalgam was undertriturated. The reduction of stress where much more mercury is initially available may be due to a lubricant action of this mercury.

Correlating the microstructure observed with the physical properties of the specimens examined it became evident that there is a relationship between the existence of an increased number of stress lines and reduced expansion of amalgam.

In none of the specimens examined was there evidence, except in rare instances of particles touching one another.

It appears that the amalgam formed, has formed on the surface of the alloy particles, which is in keeping with the present knowledge of the setting of amalgam. It is quite conceivable that the crystalline matrix which has formed contains both the dodecahedral crystals of the gamma 1 phase and the hexagonal crystals of the gamma 2 phase. It would not be possible to distinguish these two phases in a photomicrograph. That a mixture of these two phases
grown on the surface of Ag$_3$Sn has been demonstrated by Ryge et al (1961) by crystallographic means.

The presence of the phase which was etched by 30% HNO$_3$ was examined for all the specimens which were under examination.

Figure 56 shows the structure of a standard specimen and from a study of this it appears that the phase within the particles is closely associated with the surface of the particles and as this is not simply an eating into the alloy particles by the amalgam.
Following the solution of mercury this is apparently a different phase from the phase or phases occurring outside the particles. A simple reduction in the size of particles does not ensure particles which are completely replaced by this phase, and in Figure 57, which is an amalgam prepared from a fine grained alloy by the standard technique there is the same relationship between the phase within the particle and the surface as for a medium grained alloy. There is no evidence of complete ingrowth into these particles.

Fig. 57. Alloy 2, standard HNO$_3$ etch, 1000 X.
A marked increase in the amount of this phase was observed in several specimens. There was found to be an increase in specimens which had been prepared by overtrituration, where the initial ratio of mercury to alloy was reduced, where trituration was carried out at an increased temperature and where amalgam was mixed in a high energy amalgamator.

Figures 58 and 59 show amalgam specimens prepared by mortar and pestle trituration for 90 seconds and Wig-l-bug trituration for 20 seconds. Larger amounts of this internal phase were rarely seen than are seen in Fig. 59. Figure 38 which showed the structure of the typical "5:5 amalgam", shows small particles completely attacked and some large particles resistant to the formation of the internal phase.

By etching some original alloy particles it was possible to determine that this phase under consideration is related to the amalgamation process as no evidence of the phase was found in the original alloy.

An examination of specimens prepared from a high mercury: alloy ratio (9:5) showed that this phase is not entirely dependent on the presence of sufficient mercury, as Fig. 60 shows the almost complete absence of this phase in such an amalgam.
Fig. 58. Alloy 1, 90 secs. Trituration, HNO₃ etch, 1000 X.

Fig. 59. Alloy 1, 20 secs. Wig-l-bug, HNO₃ etch, 1000 X.
Fig. 60. Alloy 1, Hg:alloy 9:5, HNO₃ etch, 1000 X.

Condensation did not appear to affect the formation of this phase.

When the appearance of the HNO₃ etched specimens was compared with that of the cyanide etched ones it was obvious that specimens with a high percentage of stress lines in alloy particles also exhibit a high degree of formation of the phase within the alloy particles and that an increase in the presence of this phase occurs in specimens where a reduced expansion or contraction has occurred.

I was able to demonstrate the relationship existing between stress lines and this phase by examining the same field etched by the two techniques. Figure 61 shows the two photomicrographs resulting and
Fig. 61. Alloy 1, standard, HNO$_3$ etch, 1000 X.

cyanide etch, 1000 X.
these show that apparently the stress lines make it possible for an increased amount of the internal phase to form. Figure 61 also shows the presence of the phase in the original alloy which is not at all attacked internally, similar to the phase in Fig. 36.

Although there is a relationship between stress lines and the internal phase in the original alloy this relationship does not necessarily exist for the type of early slip planes occurring in Figure 40. A study of Fig. 62 which is the same field as Figure 40 shows this. Figure 62 also shows quite clearly that the phase within the particles is not continuous with the matrix phase. The matrix can be seen growing into the crevices where solution has obviously taken place at the surface of the particles, but there is a clear distinction between the phases inside.

Fig. 62. Alloy 1, Hg:alloy 5:5, HNO₃ etch, 1000 X.
and outside the particle. The fact that these are different phases may also be verified by the presence of the grain boundary separating them. This grain boundary has been seen to be a constant feature of specimens etched using 30% nitric acid.

A study of the microscopic structure of the alloys other than alloys 1 and 2 was carried out for some of the variables investigated.

Alloys 3 and 4 showed an identical structure to each other and typical photomicrographs are shown in Figs. 63, 64 and 65.

These alloys appeared to contain considerable numbers of stress lines which did not appear to be compatible with the expansion of these alloys. A close study of these stressed areas revealed that amalgam matrix was actually contained in them. Figure 65 shows these "stressed areas" of the alloy particles in a specimen etched using HNO₃ and the continuity with the crystalline amalgam matrix. As well as this can be seen areas of "normal" alloy particles. Following etching in the "cyanide" etch the presence of a Widmanstätten structure was observed in the original alloy particles, Fig. 66, and it is in these areas that additional attack on the particles takes place with consequent additional and rapid formation of \( \gamma_1 \) and \( \gamma_2 \) phases which may help to account for the slightly higher expansion of amalgams prepared from alloys 3 and 4.
Fig. 63. Alloy 3, standard, cyanide etch, 1000 X.

Fig. 64. Alloy 4, standard, cyanide etch, 1000 X.
Fig. 65. Alloy 3, standard, HNO₃ etch, 1000 X.

Fig. 66. Alloy 3, Original particle, cyanide etch, 1000 X.
Alloys 3 and 4 behaved exactly as alloys 1 and 2 in the normal areas of the alloy particles when submitted to manipulative variables.

Amalgams prepared from alloy 7 could not be distinguished from alloys 1 and 2. They did not exhibit the Widmanstatten structure as did alloys 3 and 4. This was a little surprising until it was realised that although theoretically from the same manufacturer, alloys 3 and 4 were manufactured in the United Kingdom and alloy 7 in the U.S.A. and the manufacturing process may be a different one.

Alloy 5 was slightly different the particles having many fine stress lines when "cyanide" etched and when etched by HNO₃ there is much evidence of the presence of the phase within the alloy particles. (Figs. 67, 68). This is in keeping with the very low expansion exhibited by amalgams prepared from this alloy. The phase within the particles appeared to be much finer than in the other alloys studied. Alloy 6, the preamalgamated alloy gave very different results from the other alloys. (See Figs. 69, 70). It was impossible to demonstrate the crystal structure of the amalgam. The appearance of the original alloy particles was different in so far as grain boundaries may be observed in these particles. This is almost certainly due to the use of mercurous salts to activate the alloy and is similar to the effect of mercurous nitrate on brass which is the method used to obtain single crystals of brass. There is a great tendency for these particles to break up along these grain
Fig. 67. Alloy 5, standard, cyanide etch, 1000 X.

Fig. 68. Alloy 5, standard, HNO₃ etch, 1000 X.
Fig. 69. Alloy 6, standard, cyanide etch, 1000 X.

Fig. 70. Alloy 6, standard, HNO₃ etch, 1000 X.
boundaries and amalgams from alloy 6 showed a much closer packing together of the alloy particles than other alloys. This does not greatly increase the strength because of the presence of mercury at the grain boundaries which would have the effect of reducing the strength of the amalgam despite the packing together of alloy particles and may also account for the markedly increased flow of this alloy.

The internal phase tends to form at the surface of the particles as these particles appear to break up rather than become stressed when subjected to additional work.

Following the examination of the microscopic structure of amalgams prepared with the seven alloys studied with a very wide variety of techniques it is obvious that wedging together of particles, rarely occurs as has been suggested. It is also observable that amalgam never becomes completely homogeneous there always remaining some original alloy particles embedded in a matrix of amalgam.

In the amalgam it is possible to distinguish three distinct phases. These phases are the original alloy particles (γ), a crystalline phase in which the alloy particles are embedded and which is associated with expansion of the amalgam. Amalgam specimens containing an increased amount of this phase tend to have increased expansion as well as reduced compressive strength. This phase quite logically may be a mixed phase and contains both γ₁ and γ₂ crystals.
It is inconceivable that only the $\gamma_2$ phase would be formed on the surface and outside the alloy particles. The third phase which is different from the matrix phase occurs within the particles and is associated with reduced expansion or contraction. This phase may be the $\beta$ phase which Gayler and Troiano claimed is present in amalgam, but which more recent workers have failed to identify. This phase may be a solid solution of mercury in the $\gamma$ phase.

There is little doubt that this is the same phase within the particles as described by Schmitt although Schmitt showed the presence of more of this phase than I have been able to demonstrate. This may be due to the fact that all photomicrographs published by Schmitt were of low silver content alloys or using a low initial mercury:alloy ratio. Present knowledge would indicate that all of these amalgams would exhibit a contraction or at least a very low expansion. Schmitt had not been able to investigate amalgams prepared using excess mercury.

Attempts were made to determine the time of formation of this phase but these failed because of the impossibility of polishing early amalgams without excessive smearing. Specimens were examined ten hours after packing and these were found to contain this phase apparently fully developed.
APPENDIX A.

MERCURY CONTENT.

Although an investigation of the mercury content of amalgam restorations, as related to manipulative variables, was not considered as a part of my investigations a series of specimens prepared by me were analysed for mercury content by Miss M. L. Swartz of the University of Indiana. These results proved to be very interesting and will be very briefly discussed.

In a series of 12 specimen types the residual mercury content ranged from 39.89% to 49.04%.

Of the 12 specimen types, 9 had a mercury content below 44% and 3 had a content above 46%.

The lowest mercury content (39.89%) was obtained by using 7:5 Hg:alloy ratio with 40 seconds triturations and was condensed by hand in 16 increments with 25 thrusts of 10 pounds on a 1.5 mm. condenser.

A specimen packed by the standard technique had a residual mercury content of 41.74%.

A fine grained alloy packed by the standard technique had a residual mercury content of 42.67%.

The effect of mercury:alloy ratio was interesting and it was
found that where an initial ratio of 9:5 was used the mercury content was 42.76% which was lower than an amalgam where an initial ratio of 5:5 was used (43.43). Analysis of increments from which mercury had been squeezed by hand resulted in percentages of 50.37 and 46.46 for ratios of 9:5 and 5:5 respectively.

Where no mercury was removed before condensation by the standard technique the residual mercury content was slightly increased to 43.83%. The failure to remove mercury before condensation assumed much more importance where a high initial ratio (9:5) was used as this followed by the standard packing procedure produced the highest mercury content of all the specimens examined, 49.04%.

Where the amalgam was overtriturated (180 seconds), the mercury content was 43.37% which was slightly more than the standard specimen.

Condensation appeared to play a major role in the removal of mercury and the use of a 3 pound load for condensation produced a residual mercury content of 46.42%. This was further increased when a 3 pound condensation load was used following an initial ratio of 9:5. This produced a mercury content of 48.52 although mercury had been squeezed from the increments to a percentage of 50.37% before condensing.

The effects of delaying condensation for 5 minutes after trituration, and of replasticizing the amalgam mix for 5 minutes making
the ratio of mercury:alloy to 9:5 were respectively values of 43.38% and 43.08% although the amount of mercury which could be squeezed from these increments resulted in mercury contents of 48.7% and 51.07% before packing.

It is apparent that there is little relationship between the residual mercury content and the mercury content of the increments before condensation and the factors affecting the residual mercury content of the amalgam most is the technique of condensation. Reduction of the initial mercury:alloy ratio to 5:5 caused a residual mercury content higher than an initial ratio of 7:5 or even 9:5, for similar methods of manipulation. There is no absolute correlation between strength and residual mercury content nor between dimensional change or flow and mercury content.
CONCLUSIONS AND DISCUSSION.

Following what has been a rather extensive investigation of the properties and microscopic structure of silver amalgam as influenced by manipulative variables, an attempt will be made to formally draw conclusions from this work and discuss some of the results presented. Many of these conclusions have been discussed in the body of this work but a formal statement of conclusions reached does require some discussion. Some of these conclusions are in the nature of verification of past work and accepted theories, while others are in direct opposition to much previous work and accepted theory. Conclusions will be considered as they affect the manipulative variables and the major physical properties.

The Variables.

It is obvious that provided an amalgam alloy is selected which complies with specifications, satisfactory properties can be developed in amalgams formed from all of these alloys, providing adequate techniques of manipulation are followed. The use of fine grained alloys in general results in a slightly higher early compressive strength than coarser alloys and this slight increase in compressive strength is maintained in fully set amalgams. No general statement is possible regarding the effect of particle size on dimensional change and alloys, similarly manufactured, but
with differing particle sizes, tended to exhibit similar dimensional change characteristics. One alloy which had a low expansion under normal conditions of manipulation was found to be very susceptible to manipulative variables from the point of view of dimensional change.

After examining the microstructure of amalgams prepared from varying sized alloys it is obvious that the influence on the surface roughness of amalgams and hence the ability to polish is negligible and particles of comparable size may be found in amalgams prepared from fine grained alloys as well as medium grained alloys. Larger particles may be found in alloys consisting of large chunky grains, which are not readily reduced in size. The largest particles observed would be most unlikely to affect the polishing potential of a restoration. It was observed that fine grained alloys exhibited better "packability" than coarser grained alloys as measured by the porosity resulting in the amalgam.

The use of a zine free alloy results in amalgams exhibiting essentially the same properties as amalgams prepared from zine containing alloys.

The effect of varying the ratio of mercury:alloy used initially is such that increasing the amount of mercury available initially lowers the compressive strength of the amalgam but increases the flow and the dimensional change of the amalgam. While a decrease in the amount of
mercury initially available has the effect of increasing the early strength and setting rate of all the amalgams tested, it has the undesirable effect of decreasing the expansion of the amalgam and it may result in a contraction at the end of 24 hours. The effect on the flow of the amalgam is negligible. Because of the deleterious effects on the dimensional change and the additional mixing (preferably in a high energy amalgamator) usually required to produce a satisfactory mix, this method of obtaining increased early compressive strength should be regarded with caution particularly in view of the fact that more mercury is retained in such amalgams than in amalgams prepared with the manufacturer's ratio. The increase in strength is almost certainly bound up with the greater efficiency in packing caused by additional resistance to the condenser of the drier amalgam. This however is offset by the use of an efficient method of removing mercury from the mix before condensing which has been shown to be of importance for the development of satisfactory physical properties.

While the addition of mercury to the mix after trituration has been shown to have no effect on the compressive strength of amalgam it has a very serious effect on the dimensional change and for this reason is contraindicated. It appears from a study of the microstructure of amalgam that the addition of mercury to the amalgam after stressing the alloy particles in the presence of mercury during mixing results in the formation of a phase within the alloy particles which is
responsible for contraction. There is no evidence that replasticizing amalgam causes a retention of additional mercury in the amalgam which would tend to produce an increased expansion.

The influence of trituration is most prominent on dimensional change, and while an increased amount of trituration increases the compressive strength of amalgam, this increased trituration acts to reduce expansion in amalgam.

The increase in strength occurs because of a breaking up of alloy particles, thereby allowing these to be more closely packed together. The reduction of expansion has been shown to be due to the formation of a contraction phase with additional stressing of particles which may account for the ability to produce a contraction without an increase in strength when trituration is carried out using mechanical amalgamators, or at elevated temperatures. Although standardised mixes may be prepared using a mechanical amalgamator, very satisfactory mixing may be carried out using a well conditioned mortar and pestle of the raised centre type. This trituration is best accomplished using a very light load and high pestle speed. The stage of trituration may be assessed visually.

Overtrituration should be avoided as much as the use of undertrituration because of the possibility of causing a contraction in the amalgam as well as difficulty in maintaining a satisfactory
mortar. To deny the importance of contraction on a clinical basis would be to deny the importance of specifications for dental materials and throw this phase of dentistry back into the nineteenth century. The importance of contraction assumes more importance in the light of recent research into marginal adaptation of restorative materials, including amalgam.

The use of a fine or controlled grain alloy does nothing to reduce contraction following overtirtration.

Tirituration by means of a finger stall produced results which were far too widely scattered to allow any conclusions to be drawn about this method of trituration.

Condensation may be equally well carried out using hand pressure or a mechanical vibrating condenser but no advantage is gained by the use of a mechanical condenser.

Condensation is not a function of pressure as such and very many factors are involved in adequate condensation. To speak of increasing condensation pressure and the importance of reducing condenser size to increase the pressure for the same force takes no account of the importance of the size of the cavity in relation to the size of the condenser, the number of thrusts used, the number and size of the increments used.
From a study of the physical properties and the microscopic structure of amalgam it is obvious that a condenser can be moved only a short distance through amalgam before it is brought to rest and the distance which it can move is largely governed by the size of the condenser, in relation to the cavity.

Condensation may be thought of as work carried out on the amalgam in order to condense it.

Since \( W = F \times s \) we can increase the work by increasing the force or increasing the distance through which the point of application of the force moves. If the condenser fails to move as happens with a very low condensation load or a very large condenser no work is done on the amalgam. On the other hand if too small a condenser is used, the force will not be effective in condensing the amalgam as it simply spreads it aside. Having selected a condenser which will move through the amalgam with resistance we can increase the distance this moves by increasing the time of application of the load which allows the condenser to continue to move though almost imperceptibly. A more effective method of increasing the distance travelled is to increase the number of thrusts of the condenser and where relatively low loads are used this is of considerable importance.

Without doubt the most important factor in the condensation of amalgam is the size of the pieces of amalgam introduced into the
cavity. Where very low condensation loads, as may be the case in clinical practice, are used, the size of the increments assumes even more importance, as a very small increment may be completely condensed through its whole thickness by even a small load.

Ideal condensation can probably be carried out using a fairly high load, very small pieces and a large number of thrusts on a condenser which will move through the amalgam but will be resisted by the amalgam. The size of the condenser is governed by the size of the cavity and in a clinical cavity a condenser of diameter 0.5 mm. is frequently very effective whereas one of 1.5 mm. would not be able to adequately penetrate the amalgam.

It has been shown that strengths comparable to those produced by overtrituration and low mercury:alloy ratio may be produced by an adequate packing technique and since this may be achieved without the production of a contraction this is the method which should be used.

In the condensation of the clinical Class II restoration the use of several small pieces of amalgam to fill the proximal box portion cannot be overstressed. Filling this in one piece produces a restoration which may be completely uncondensed at the gingival margin and which may be porous in the manner of the specimens packed by hand in one piece with 200 thrusts in my investigation. Porosity in this region would not be eliminated during polishing and may give rise to galvanic action
with its associated effects on the amalgam, and general poor hygiene in this area.

From the evidence obtained from the microscopic structure in support of studies of the physical properties of amalgam there is no evidence that there is a real advantage in using a multiple mix technique in the packing of large amalgams, provided that mercury removal is carried out from increments of the mix.

The use of retention wires in amalgam causes a reduction in compressive strength of amalgam but in clinical restorations the retention value may outweigh the strength reduction. Care should be taken to keep the wires short and close to the pulpal wall of the cavity where the amalgam will be best supported and also as few in number as possible which also facilitates condensation.

Moisture contamination of amalgam influences only dimensional change, the effect on the compressive strength, polishing ability, and microstructure of amalgam are negligible.

In polishing amalgam clinically we are able to take advantage of the tendency for amalgam to smear and the surface may be rendered most homogeneous by the use of slow cutting abrasives. Blunt plug finishing burs followed by a very slowly revolving brush, charged with pumice at a fairly high load will close over any holes in the surface. The high lustre can then be given using a fine polishing agent at very light
pressure and a high speed. When the surface has been rendered homo-
geneous this may be effected in a very short time.

The Properties.

Dimensional change is obviously a very complex procedure and
is almost certainly controlled by a combination of many factors.

From a study of the microstructure of amalgam it appears
that during trituration solution occurs at the surface of alloy
particles which may result in the "eroding of particles" and the
formation outside the particles of the gamma 1 and gamma 2 phases
which produce expanding conditions. This surface solution does not
at any stage after condensation produce a contraction because the
formation of the expanding phases within the amalgam has begun and
overcomes this very rapidly. This would explain why fine grained
alloys do not expand less than coarser particles. If surface solution
caused contraction it would be reasonable to expect that where more
mercury is available for solution, as in a high initial mercury:alloy
ratio amalgam or during condensation with a low load, there would be
a tendency towards contraction, which of course is not the case. At
the same time, but more slowly, another phase (possibly a solid
solution of mercury in gamma) is forming within the particles which
is responsible for contracting conditions.
Throughout setting there is a balance between these factors and at times the formation of the contraction phase may be greater than the expanding phases and cause an obvious contraction. At other times there may be no contraction measured, but the rate of expansion may be slowed. If the formation of the contraction phase continues after the completion of the formation of gamma 1 and gamma 2 phases a secondary contraction may result.

The reason for the great influence of mulling and the late addition of mercury on dimensional change may be that more mercury is made available for the formation of the contraction phase within the stressed particles.

The reason for the lowered expansion of very thin particles, lies I think in the greater ability of these particles to be stressed during manipulation.

Compressive strength depends on porosity which is present in amalgam as well as on the mercury content of the amalgam. While the porosity is reduced slightly by overtrituration (or at least more widely dispersed) the most effective means of reducing porosity and consequently increasing compressive strength, particularly at one hour is by an increase in condensation.

Flow of amalgam has frequently been shown to be not a clinical
factor in amalgam restorations and the sole reason for its retention in specifications appears to be on the grounds of a measure of strength. This property bears no constant relationship to the early strength of amalgam or the strength during setting or at the time of complete set and because of this would appear to be of little value in the assessment of amalgam alloys.

The microscopic structure of amalgam is revealed to be most heterogeneous. Amalgam consists of a crystalline matrix, which is almost certainly a combination of the gamma 1 and gamma 2 phases, original alloy particles the gamma phase and a fourth phase which forms within the original alloy particles and may be the beta 1 phase. The crystals in the $\gamma_1$, $\gamma_2$ areas are very small being approximately 1 - 2 microns in "diameter". All amalgams also contain voids which will influence the strength of the amalgam. These voids are related to the technique of manipulation.

Although they are remarkably homogeneous, considering the complex nature of the alloy, the original alloy particles from all manufacturers contain some phases other than the gamma phase of silver tin $\text{Ag}_2\text{Sn}$. 
SUMMARY.

1. An extensive investigation of the effects of many manipulative variables on the physical properties and the microscopic structure of amalgam has been carried out and the results correlated where necessary.

2. The ability to produce satisfactory amalgam from a wide range of specified alloys has been shown.

3. The effects of varying the initial mercury:alloy ratio have been studied.

4. The importance of adequate trituratation has been demonstrated and the relationship of trituratation to all the physical properties but particularly dimensional change has been shown.

5. A rationale for the condensation of amalgam has been considered and a method of producing very high strength amalgams with very low mercury content, without an associated contraction has been proposed.

6. The variables of moisture contamination, reinforcement and temperature of setting have been investigated.
7. Flow has been shown to bear little relationship to the other properties of amalgam.

8. Methods for the metallographic polishing and etching of amalgam have been described and the findings using these etchants have been correlated.

9. A series of photomicrographs showing the effects of manipulative variables on the microscopic structure of amalgam has been produced, at several magnifications.

10. A possible theory of dimensional change has been proposed, and a comment made on the measurement of dimensional change.
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