Dental amalgam has been the main restorative filling material for dentistry for almost 180 years in the United States (since about 1830). Due to better-and-better alternatives and increasing concerns for amalgam/mercury recycling challenges, the relative use of amalgam in first world countries is decreasing. A special caveat should be added. As dental care delivery increases in second and third world regions, dental amalgam is often the first tier strategy for treatment of dental caries. The actual amount of dental amalgam sold in the entire world actually continues to increase, despite the fact that its preference decreases. [In the slide above, the alchemist’s symbols are shown for mercury (left) and amalgam (right).]
Amalgams are primarily used in posterior sites in the mouth. While they were used for virtually all operative sites about 30 years ago, there has been a strong shift toward anterior esthetics. Amalgams are used for Class I and II sites and for cores/foundations. Otherwise, tooth colored filling materials are preferred instead. If the Class I and II sites are relatively small, then composites are often used as alternatives. Many existing amalgam restorations may look a little harried at the margins but that is generally not a reason for replacing them.
**AMALGAM TERMINOLOGY**

**AMALGAM** = an alloy containing Hg as the major ingredient.

**DENTAL AMALGAM** = an alloy of Hg with Ag-Sn.

**DENTAL AMALGAM ALLOY** = a Ag-Sn alloy (to be mixed with Hg).

An “amalgam” means any material containing Hg as a major ingredient (element) in the composition. A specific composition based on mixing Ag-Sn alloys with Hg is called a “dental amalgam.” The Ag-Sn alloys are referenced as the “dental amalgam alloy.”

The reaction is shown schematically above. Upon mixing the mercury begins to dissolve and react with the outer layers of the Ag-Sn particles (which are generally polycrystalline). About 15% of the Ag-Sn particles are consumed to produce complete reaction of the Hg and generate a matrix of solid reaction products. The specific products will be addressed in a second. The primary product is composed of Ag-Hg. The unreacted alloy particles remain embedded within the matrix and contribute mechanical reinforcement. In addition the dispersed particles have better corrosion resistance than the matrix.
Alloy is produced predominantly as irregular-shaped, spherical particles, or mixture of the two types. Irregular particles are generally “lathe-cut,” meaning that the cast brick or ingot of material is pulverized by filing on a lathe. The pieces are polycrystalline and tend to have flat faces representing the sheared planes created by filing. In most cases the ingots are cooled relatively quickly and require heat-treatment to remove coring. Because of the large amount of plastic deformation during filing, the particles require annealing to relieve the cold work. Both of these occur during the post-filing heat treatment.

Spherical particles are created by atomizing or spraying liquid dental amalgam alloy through a nozzle into a vertical column of cooled nitrogen gas. This solidifies the spheres and protects them from oxidation during the cooling steps. After the solid spheres are formed, they are generally acid washed and heat-treated to remove coring.
During the placement of dental amalgam, the plastic mass (that is still solidifying) is compressed (condensation) to extrude excess matrix from the setting mass. This is important because the matrix phase is the weaker and more corrosion prone than the residual alloy particles. Thus, the initial mercury to alloy ratio is not absolutely important. However, a mixture with the least amount of mercury is more likely to have the least amount of final matrix after condensation. The graph above reports the general change in Hg:alloy ratio (see the numbers on the curve) and the corresponding weight percent of mercury (y-axis). Most contemporary mixtures are now made with 45-50% initial mercury and end up with about 42% after the reaction and condensation steps are complete.
ALLOY MANIPULATION

Manual Trituration Procedures:
Alloy + Hg → mortar + pestle → manual mixing

Mechanical Trituration Procedures:
Powdered alloy + Hg → capsule + pestle → amalgamator
Pelleted alloy + Hg → capsule + pestle → amalgamator
Powdered alloy + Hg → pre-capsulated → amalgamator

A historical review of mixing dental amalgam is portrayed in the figure above. In early times, the powder particles of dental amalgam alloy and mercury were simply combined at the dentist’s discretion. However, by the late 1890s there was early scientific evidence that better amalgams resulted from proportioned materials. The small black bakelite balance shown in the upper left hand corner was in use in dentistry in the 1920s. The center of the rocker arm was adjusted to the desired Hg:alloy ratio. The arm contained a small groove allowing Hg to run from one end (left) to the other (right). Hg was proportioned on the left-hand rocker cup. Then alloy was added slowly to the right-hand cup. As soon as the proper ratio was achieved, it tipped the rocker arm and the Hg ran from the left to the right. This combination was then manually mixed in a mortar-and-pestle and carried to the cavity preparation for condensation.

While this process could be consistently accomplished it was difficult for all operators to manually mix the mass in an equal manner. Therefore, in the late 1940s and early 1950s mixing (trituration) was accomplished using a mixing capsule with an internal steel pestle that was shaken back and forth in a figure-8 pattern to replace the action of the mortar and pestle. This was much more reproducible. To more easily load the capsule, the alloy powder was pressed into a pill under pressure that could easily be dispensed from a tube of pills. The Hg was proportioned as a spill (droplet) that was calibrated to the pill to preserve the Hg:alloy ratio recommended by the manufacturer. In the late 1960s and early 1970s, pre-proportioned capsules containing alloy powder and Hg appeared. The materials were separated by a thin foil barrier that was broken by twisting or pressing the ends of the capsule to allow them to come into contact just before trituration. The figure at the middle of the bottom of the frame above shows the large variety of designs available. While delivery of the materials in a disposable capsule is more expensive, it saves time, and tends to minimize the opportunity for Hg vapor to escape into the dental operatory.

Newer amalgamators have a cover over the jaws that grab the capsule and produce the mixing motion so that any spillage is prevented from become aerosolized in the region of the dentist and/or dental assistant. However, small amounts of Hg or mixture may still be spilled from the bottom of the mixing equipment.
Early dental amalgams (1900-1965) contained less than 5% copper and historically had limited corrosion resistance. In 1965, the first higher copper (high-copper, 12-30%) amalgams were commercialized after it was discovered that they were much more corrosion resistant. A large part of the classification scheme for dental amalgams is related to the copper addition to the alloy powders. The major classification is simply based on copper content, low copper versus high copper. Low copper dental amalgams were primarily made by filing particles from an ingot and were irregular-shaped. In the late 1950s and early 1960s, more and more spherical versions of the same alloys appeared on the market. Generally the texture of the setting amalgam was one of more crunchy feeling during condensation if irregular particles were involved. Spherical amalgams were lower viscosity. The very first high copper amalgams (Dispersalloy, Johnson & Johnson) actually added the copper as a Cu-Ag eutectic sphere to the Ag-Sn irregular particles. Other high-copper products (Tytin, Kerr) mixed the Ag-Sn-Cu in the same spherical particles. Regardless of how the elements are actually presented to the mixture, the same overall setting reaction takes place. Examples of two different low and high copper products are shown above.

Finally, small amounts of Zn (0.2-0.5%) were traditionally added to the alloy to protect the mixture from oxidation during melting and casting of the ingots or spheres. It was discovered that if setting amalgams were prematurely contaminated by water from mixing or condensation, that it was possible for water to react with Zn producing ZnO and H₂ gas. The hydrogen gas would increase expansion during setting and could contribute to tooth fracture. If the amalgam mixture was carefully manipulated this did not occur. In long term clinical trials, the presence of small amounts of Zn seems to contribute to ZnO production at cavity walls and margins and discourage corrosion, thereby increasing longevity.
Individual compositions can produce quite complicated dental amalgam microstructures but basically the same important phases are present in all systems. As shown above on the left for cases of irregular and spherical alloys, the residual dental amalgam alloy powder particles are gray islands within the continuous matrix of reaction products that appear in white. The reaction products are about 90% Ag-Hg and either 10% Ag-Sn (low copper) or Cu-Sn (high-copper). The overall functions of each of the reactants is reported on the right-hand size of the slide. The SEM micrograph shows a high-resolution image of a spherical particle with a complex reaction zone surrounded by Ag-Hg grains in the matrix and some evidence of porosity from inadequate condensation.
### SETTING REACTIONS

**Low-Copper Dental Amalgam:**

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Product 1</th>
<th>Product 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>I/S-Alloy + Hg → Residual Alloy</td>
<td>+ Matrix-1</td>
<td>+ Matrix-2</td>
</tr>
<tr>
<td>Ag-Sn + Hg → Ag-Sn</td>
<td>+ Ag-Hg</td>
<td>+ Sn-Hg</td>
</tr>
<tr>
<td>Ag₃Sn + Hg → Ag₃Sn</td>
<td>+ Ag₂Hg₃</td>
<td>+ Sn₇-₈Hg</td>
</tr>
<tr>
<td>γ + Hg → γ</td>
<td>+ γ₁</td>
<td>+ γ₂</td>
</tr>
</tbody>
</table>

**1-Particle High-Copper Dental Amalgam:**

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Product 1</th>
<th>Product 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-Alloy + Hg → Residual Alloy</td>
<td>+ Matrix-1</td>
<td>+ Matrix-2</td>
</tr>
<tr>
<td>Ag₃Sn/Cu+ Hg → Ag₃Sn/Cu</td>
<td>+ Ag₂Hg₃</td>
<td>+ CuSn + Cu₃Sn</td>
</tr>
<tr>
<td>γ + Hg → γ</td>
<td>+ γ₁</td>
<td>+ ε + η</td>
</tr>
</tbody>
</table>

**2-Particle High-Copper Dental Amalgam:**

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Product 1</th>
<th>Product 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-Alloy + Hg → Residual Alloy</td>
<td>+ Matrix-1</td>
<td>+ Matrix-2</td>
</tr>
<tr>
<td>γ + Hg → γ (Ag₃Sn)</td>
<td>+ γ₁</td>
<td>+ (γ₂)</td>
</tr>
<tr>
<td>S-Alloy + Hg → Residual Alloy</td>
<td>+ Matrix-1</td>
<td>+ Matrix-2</td>
</tr>
<tr>
<td>Alloy + Hg → Alloy (Ag-Cu)</td>
<td>+ γ₁</td>
<td>+ ε + η</td>
</tr>
</tbody>
</table>

The specific reactions for both low-copper and high-copper amalgams are shown above in several ways – descriptively, using the chemical formulas for the phases involved, and using the Greek symbols for the phases. In low-copper amalgams the residual particles (Ag-Sn or Ag₃Sn or γ) react with Hg to form a matrix of Ag-Hg (Ag₂Sn₃ or γ₁) and Sn-Hg (Sn₇-₈Hg or γ₂). The Sn-Hg phase is the most corrosion prone phase but is minimized or eliminated in high-copper dental amalgams when the copper preferentially reacts with the Sn forming Cu-Sn. This phase can exist as Cu-Sn or Cu₃Sn and may be abbreviated as ε or η, respectively.
As shown earlier, the reaction can be schematically described in terms of dispersed alloy particles mixed with mercury that produce a matrix of mercury reaction products surrounding residual dental amalgam alloy particles. Of special interest is the actual geometry of the phases that are involved. The Ag-Hg ($\gamma_1$) crystals (grains) are relatively equiaxed as shown in the figure. Contrary to these grains, Sn-Hg ($\gamma_2$) crystals are elongated and look like tongue-depressor blades. This has a major consequence for corrosion. While the Sn-Hg crystals represent relatively little total volume of the mixtures, they tend to be touching (connected) throughout the entire dental amalgam allowing penetrating corrosion to take place. Shifting to high-copper amalgam has both the advantage that Cu-Sn is less corrosion prone and the grains do not routinely touch each other, so that only superficial corrosion occurs.
The reaction of a typical 2-particle high-copper dental amalgam is schematically summarized above. Ag-Sn-(Zn) irregular particles are mixed with Ag-Cu spheres to produce the amalgam alloy. Mixed with Hg, Ag-Hg and Sn-Hg phases form. Almost as quickly as Sn-Hg forms, the phase is eliminated by the competitive reaction of Cu with Sn. As Cu3Sn or Cu-Sn forms, then the release Hg reacts with more Ag-Sn to produce predominantly Ag-Hg. Therefore, little or no Sn-Hg resides in the set amalgam as shown in the microstructural analysis above.
Ag-Hg is a complex phase diagram. Most of the reaction product for the amalgam setting reaction is Ag-Hg around the stoichiometric composition for Ag₂Hg₃ which is 60 atomic percent Hg. By looking at the scale along the top of the phase diagram, one can see that 40Ag-60Hg in atomic percent corresponds to about 34Ag-66Hg in weight percent. At room temperature, on the phase diagram at 40Ag-60Hg occurs a narrow single phase region labeled gamma-1. Therefore, the matrix phase (which is almost exactly this composition) is often described as gamma-1 crystals. The actual composition of individual crystals may vary somewhat depending on the nucleation and growth conditions.
The entire sequence for restoration with dental amalgam involves quite a few steps. Almost without exception, high copper dental amalgam is selected as the material of choice. Every product is available in a precapsulated form. After proper trituratum in a mechanical amalgamator, a shiny pliable mass is removed from the capsule, temporarily placed in a small dish (dappen dish) to facilitate loading of an amalgam carrier to transport the material the cavity preparation. The plunger of the carrier pushes the fluid mass into the cavity. Quickly and efficiently the mass is compressed with an amalgam condenser (double-ended stainless steel hand instrument with a small and large nib on the ends). The large end is used initially (low stress = load / large area) followed by the smaller nib (high stress = load / small area). This compresses the particles of residual alloy together, expressing the unset Hg-rich matrix for removal from the restoration surface. This minimizes the final amount of matrix in the restoration and increases the strength and fatigue resistance. After slightly overfilling the cavity preparation, the surface is contoured with an amalgam carver. The blade of the carver is moved parallel to the margins to use the enamel surface as a guide and insure that the carved surface is confluent with the adjacent enamel. As this surface begins to harden (after just a few minutes), it is compressed with a ball burnisher to smoothen it. At this point, the amalgam is still relatively weak and unsuitable for final polishing. At the next recall or dental hygiene appointment, the amalgam is typically polished with a series of finer and finer abrasive polishing points and abrasives. This creates a very shiny surface, although this surface is no more effective in corrosion resistance that the burnished one. This has been demonstrated in numerous long-term clinical trials.
Now let’s consider some of the special features of the steps in amalgam placement. As shown above (left = older amalgamator = Caulk VariMix), each mechanical amalgamator has options for setting the speed (rpm of the capsule throw, typically 3000-4000 rpm) and time (seconds of mixing time, typically 8-10s). Increasing the speed or amount of time will increase the total mixing energy. Each amalgam product has a special combination of speed and time to produce good mixing without over-mixing. A well-mixed amalgam should be fluid, bright, and shiny. An over- or under-mixed mass will be dry in appearance and should be discarded.
As described earlier, the condensation step forces the residual amalgam allow together, expressing the fluid unset Hg-rich matrix to the surface for removal. When setting does occur, the matrix will consist almost entirely of small gamma-1 (Ag-Hg, Ag2Hg3) crystals (as shown in the figure on the right). As setting starts to occur the texture of the mass changes to one of substantial resistance to condensation.
The setting reaction involves a complex series of reactions occurring at different rates and producing different local volume changes in the mass. Dissolving the amalgam alloy into Hg and formation of Ag-Hg crystals leads to a slight decrease in volume (contraction). However, the growing crystals push on each other and create expansion. Depending on the time of condensation and extent of reaction, the volume change may vary anywhere from -20 to +20 microns per cm over the setting reaction. Over long periods of time (weeks to a month) the reaction will slowly continue and can produce small amounts of solid state creep as well.
AMALGAM PROPERTIES

A. Introduction:
   1. Specifications for Amalgam Properties
      a. ADA / ANSI and ISO
   2. Clinical Performance
      a. Longevity = 20-25 yrs ideally, 8-12 yrs practically
      b. Modes of failure = caries, marginal fracture, bulk

B. Properties:
   1. Physical
   2. Mechanical
   3. Chemical
   4. Biological

The properties of dental amalgam should be collected in the standard manner as physical, mechanical, chemical, and biological ones. Despite our general interest in all 35-40 properties, there are a few which are important because they establish the extent of reaction and minimum suitability of the material for clinical use. These few properties are used as laboratory standards for amalgam products. ADA/ANSI and ISO standards indicate specifications for acceptable products for safety and efficacy.

In the small figure in the lower right in the slide above, the general relationship of these organizations is indicated. The ADA is the national dental association for the United States. It, like all other organizations with standards, files its standards with the American National Standards Institute (sort of the registry for all standards). The FDI (Federation Dentaire International) is the collection of all national dental associations. It files its standards with the ISO (International Standards Organization).

Standards do not guarantee the longevity of any restoration. Measured clinical performance is observed in controlled clinical trials and also in general dental practice. The latter results are often only about 40% as great (8-12y) as that for controlled clinical trials (20-25y). While secondary dental caries may be associated with amalgam restorations, primarily failure occurs by bulk fracture due to fatigue.

Now let's consider the individual categories of properties of amalgam.
### Physical Properties

1. Thermal conductivity = [High]
2. Electrical conductivity = [High]
3. Coefficient of thermal expansion = 25 ppm/°C
4. Radiopacity = [>2 mm Aluminum]
5. Color = [Lustrous, shiny, white]

Generally amalgam restorations are considered esthetic (although not tooth-colored) restorations due to the shiny, lustrous surface that reflects the white color of neighboring teeth in the mirror-like finish. All metallic restorations are greater in radiopacity (radiodensity) than enamel or dentin. Since restorative materials are traditionally compared to the radiopacity of 2mm of aluminum (equivalent to enamel/dentin), the radiopacity is reported as >2mm Al. Like all metals, dental amalgam is thermally and electrically conductive compared to the relatively insulating properties of enamel and dentin. As long as there is at least 2 mm of insulating restorative material and/or dentin below a restoration, there is very little chance of thermal insults to pulpal tissue during thermal transients in the mouth. The most important problem for metallic restorations is that they have different coefficients of thermal expansion/contraction (amalgam = 25 ppm/°C) compared to tooth structure (10 ppm/°C). During reductions in intraoral temperature, there is a strong tendency at the margins for amalgam restorations to contract away from the margins and allow marginal leakage of intraoral fluids (percolatoin) that are later expelled when the temperature returns to normal.
### Mechanical Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Compressive Strength (psi)</th>
<th>Tensile Strength (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10-min 1-hr 24-hr</td>
<td>10-min 1-hr 24-hr</td>
</tr>
<tr>
<td>LOW COPPER:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Velvalloy</td>
<td>5,400 17,400 56,200</td>
<td>625 1,900 9,000</td>
</tr>
<tr>
<td>Spheralloy</td>
<td>5,800 18,500 56,900</td>
<td>450 1,550 8,800</td>
</tr>
<tr>
<td>HIGH COPPER:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optalloy II</td>
<td>9,100 23,800 55,900</td>
<td>1,000 2,350 7,250</td>
</tr>
<tr>
<td>Dispersalloy</td>
<td>6,200 22,400 59,900</td>
<td>575 1,750 6,990</td>
</tr>
<tr>
<td>Indiloy</td>
<td>4,600 26,300 64,500</td>
<td>450 2,400 6,500</td>
</tr>
<tr>
<td>Sybraloy</td>
<td>23,800 50,000 72,700</td>
<td>2,190 4,700 6,600</td>
</tr>
<tr>
<td>Tytin</td>
<td>10,200 40,800 79,100</td>
<td>990 4,000 9,300</td>
</tr>
</tbody>
</table>

Probably the most important characteristic of dental amalgam is its comparatively high strength compared to tooth structure. Dental enamel has a compressive strength of ~60,000 psi (~400 MPa). Amalgam is as great or greater than that value. In the figure above, the compressive (CS) and tensile (TS) strengths of several low copper and high copper amalgams are reported. The TS values are much lower than the CS values indicating the low resistance to fracture.

During the setting reaction for amalgam, the strength does not increase quickly to near final levels. In many products, it takes several hours to get to 50-75% of the final strengths. Final strengths may not be realized for 30 days. Therefore, it is common to remind the patient to avoid creating any excessive stresses on the restoration for a day or so. Tytin (spherical high copper dental amalgam) is famous for its high early strength. It is used by 50-60% of all dentists for that reason.
Shown above is the microstructure of TYTIN amalgam alloy powder (image below) and set amalgam (image above). The alloy particles are spherical and range in size from about 5 to 50 µm. In the set amalgam, two faces are shown (polished and fractured). In the polished view, the residual alloy particles can be seen dispersed in a matrix of grey-colored Ag-Hg crystals that are weaker. In the fractured view, the fracture proceeds only through the matrix (going around all the alloy particles). This emphasizes the importance of condensing the setting amalgam as well as possible to minimize the matrix and make the path of any fracture more tortuous. Good condensation can almost double the fracture resistance of an amalgam.
Dental amalgam restorations undergo both chemical and electrochemical corrosion. Chemical corrosion principally involves the reaction of Ag on the surfaces (Ag-Sn-Cu or Ag-Hg phases) with sulfur in the saliva from air pollution or food compounds. A very thin surface film develops that is very tight, adherent, and tough. While it is not very esthetic, it is not harmful either and does not cause long-term problems. Clinical trials of tarnished versus polished amalgams over 20 years indicate that there is no important clinical effect. Shown in the figure above is a tarnished Class V amalgam on the lingual surface of an incisor.

Electrochemical corrosion is much more destructive. Amalgams (multiple phases and more electronegative than any other metal they may be in contact with) act as anodes which are susceptible to relative high corrosion rates. They may undergo galvanic corrosion (amalgam coupled to gold casting alloys), local galvanic corrosion (Ag-Hg versus Ag-Sn-Cu phase), crevice corrosion (amalgam margins or areas under plaque), and stress corrosion (occlusal and proximal contact areas).
There are a number of possible biological reactions that may be caused by dental amalgam (as shown above). Hg is released in minute levels (by sublimation from the solid state) during chewing. However, the amounts are so low and for such short periods of time that the material represents no health hazard. What is released is assumed to be swallowed and passes harmlessly through the GI tract. The details of absorption will be discussed later. A very small number (<1 in 100,000,000 patients) may be allergic to Hg. The reactions are low level (not life threatening). During the removal of amalgam restorations, small particles are spewed away from the restored site. If there is inadequate isolation (rubber dam or cotton rolls), small pieces may become embedded into soft tissues and ultimately corrode. The light gray shadow that is generated is called an amalgam tattoo. This is very uncommon with today’s high-speed handpieces, good water cooling, and use of adequate isolation.
Clinical Performance

Reasons for Failure:
- **Secondary caries** -- principally with low-copper amalgam
- **Marginal fracture** -- prevalent with low-copper amalgam
- **Bulk fracture** -- most common with high-copper amalgam

Jorgensen theory of mercuroscopic expansion

The clinical performance of dental amalgam is closely allied with its relative corrosion resistance. Low copper dental amalgams would undergo continual electrochemical corrosion of the gamma-2 phase (Sn-Hg crystals that are long and needle-like) that undermine the entire microstructure of the restoration. This resulted in low strength and extensive marginal deterioration that usually permitted secondary caries to occur. High copper dental amalgam corrode only superficially. Both low and high copper dental amalgams produce corrosion products of Sn-O (solid) and Sn-O-Cl crystals (soluble). Solid corrosion products help to seal the existing marginal crevices. Over long terms continuing amalgam reaction causes creep. If corrosion is also occurring then, as Sn is consumed, Hg is available to locally react with residual Ag-Sn and produce more Ag-Hg. This leads to expansion (and creep). Creep extrudes amalgam margins above the normal anatomic contours and allows local stresses to fracture the margins. This creates an amalgam ditch. As corrosion occurs the general margin appearance may become more and more dramatic.
For low copper dental amalgams, Dr. David Mahler developed a visual scale (1-11) using 5 photographs of progressively more deteriorated restoration margins (see the figure above from left-to-right). The scale was used to rate amalgams of existing restorations. For low copper dental amalgams the restorations proceeded from 1 to 5. In the range of 3 to 5 the amalgam was often replaced anticipating potential secondary caries. With high copper dental amalgams, the margins rarely go beyond a rating of 3 since only superficial corrosion occurs. In the absence of continual and extensive corrosion, margins do not become much worse. Therefore, they should not be replaced. On average, high copper dental amalgam restorations last approximately 24 years. The percent survival data for low and high copper dental amalgams is shown in the figure. Amalgams with Zn in the composition appear to do a little bit better, presumably due to Zn forming ZnO and sealing the margins.
Thank you.