

**SIERRA**  
CIRCUITS

# A PRACTICAL GUIDE TO **FLUX** eBook

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For more than 40 years, I have been teaching that perfect soldering is easy – the solder will do the work. However, most people who have not attended one of my *Science of Soldering*® classes do not find soldering all that easy and question my sanity. So let me add this clarification: Perfect soldering is easy *provided we make it easy*. The hard part is learning what makes soldering easy. And perhaps nothing is more important than understanding flux selection and proper usage.

There's no shortage of articles about flux on the Internet. Unfortunately, most (not all, but most) of the free advice is worth exactly what it costs. Dozens of manufacturers each sell dozens of flux formulations, almost all of those formulations being proprietary secrets that the customer won't know, and they all post marketing materials making claims that can be misleading and, in some cases, fraudulent. (Beware of "neutral pH" flux.) Anyone who knows enough to distinguish between what is valid and what is junk probably doesn't need the research. The truly meaningful literature about flux (some of it free on the Internet but often behind paywalls) is written by chemists for chemists and completely unintelligible to the people who actually use the flux. Even the terminology can be impenetrable. The following, in plain English, is the heart of what users need to know about:

- Why flux is needed
- The ingredients of flux and what they do
- Flux categories
- How to read a flux manufacturer's technical data
- The best flux for various applications

## WETTING

Understanding flux requires comprehension of what it does. As with most things related to soldering, that begins with wetting forces.

Solder flow is called wetting. When solder flows over a surface like a component lead, it is said to "wet" the surface. Failure to flow is non-wetting. What many people call "cold solder" actually has nothing to do with lack of heat; it is simply non-wetting. (I prefer the term I learned in Britain: "dry joint.")

Four natural forces determine the amount of wetting. Two of those forces work against solder flow and are called "negative wetting forces." They are:

### Surface Tension

Atoms on the surface of a liquid are attracted to atoms within the liquid. Some liquids have very low surface tension while others have higher surface tension. To see the difference, pour a little alcohol (very low surface tension) on a non-porous surface like glass. Then do the same with water (much greater surface tension). Alcohol flattens and spreads easily while water tends to bead up. Solder's surface tension is much stronger than water's (and greater with lead-free solder than leaded solder) and causes solder to form a sphere (the familiar "solder ball"). Surface tension is the most powerful negative wetting force.

## Friction

Resistance as an object moves over the surface of another object is called “static friction.” But friction also exists within liquids (“viscosity”). Both forces work against solder wetting, with viscosity being the more powerful. However, friction is less consequential than surface tension. Both forces work against solder wetting but are less consequential than surface tension.

## Gravity

The third force, gravity, helps or impedes wetting depending on the position of the surface with respect to the point of solder application. Gravity helps wetting at and below where the solder is applied (into plated holes if hand soldering, for example) but works against wetting above the solder application point (fighting the vertical fill of plated through-holes in wave soldering).

## Interatomic Attraction

The sum of surface tension, friction and gravity is negative, meaning non-wetting. A fourth force, positive and stronger than the sum of the other three, is required for wetting. That force is interatomic attraction between pure surface metal and solder. Note the emphasis on pure (elemental) metal. The atoms of metals that are good electrical conductors are unstable; they want to combine with other element(s) to share electrons. The resulting compounds have no reactive energy (the usual term is “passive”) and will not attract solder.

When solder is applied to a pure metal surface, there will be strong attraction between the surface metal and tin (the solder). The attraction exceeds the negative wetting forces and the solder wets, flowing onto pads and leads or up PTHs. At the same time, a chemical reaction between the tin and surface metal creates a compound known as an intermetallic bond. In the case of copper, the resulting intermetallic consists of 3 copper atoms combined with one atom of tin (i.e.,  $\text{Cu}_3\text{Sn}$ ) with a melting temperature of 1248°F/676°C.<sup>2</sup>

## OXIDATION AND DEOXIDATION<sup>3</sup>

Wetting occurs only when solder is applied to pure metal. But the metal surfaces (except gold<sup>4</sup>) of normal components are not pure metal; they are covered by an inert compound – metal oxide. To achieve wetting, the oxide must be removed before application of the solder.

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1. Most lead-free solders consist primarily of tin. The lead in tin/lead solder is relatively inert compared with tin.
  2. More accurately,  $\text{Cu}_3\text{Sn}$  is created when the solder is liquid. Intermetallic in the form  $\text{Cu}_6\text{Sn}_5$  with a melting temperature of 779°F/415°C continues to form at a very slow rate after the solder freezes.
  3. Oxidation originally meant the formation of a new substance by the addition of oxygen. For metals, this results in transfer of electrons from the metal to oxygen. Chemists now use “oxidation” to mean loss of electrons by an atom when forming a molecule even if oxygen is not involved. When metals combine with oxygen, the metals lose electrons to the oxygen.
  4. Gold does not oxidize. It does, however, react with some other elements, such as sulfur to form sulfides that, like oxides, are passive and must be removed before application of the solder.

Metal oxides are created by chemical reaction between metal atoms and oxygen atoms. **The reaction (“oxidation”) begins instantly whenever a pure metal surface is exposed to oxygen.** The oxide layer produced in that instant is enough to prevent the necessary contact between solder atoms and elemental metal beneath the oxide. However, oxidation may not stop with surface oxidation. Further oxidation will continue as long as oxygen atoms can reach metal atoms under the oxide.

At a molecular level, the oxide layer is not a continuous sheet like a table top; it is porous. Think of it as analogous to a window screen. If the oxide pores are larger than oxygen atoms, oxygen will pass through the pores to the pure metal underneath and create more oxide.<sup>5</sup>

Oxide porosity depends on the metal. Iron oxide (rust) has large pores while those of stainless steel (an alloy consisting largely of iron) are smaller than oxygen molecules. The difference in porosity explains why iron eventually undergoes complete oxidation (“rust”) while stainless steel remains stainless; the stainless steel oxide layer protects the underlying metal from oxygen and further oxidation cannot occur. In contrast, oxygen moves easily through porous rust to reach any remaining pure iron.<sup>6</sup>

Copper and tin can oxidize more thoroughly than stainless steel but eventually the pores close and oxidation stops. Again, it helps to think of the oxide layer in terms of window screens. A single window screen is permeable but stacking many screens with just a slight offset of each eventually forms an impenetrable barrier.

Also important, the attractive force between metal and oxygen varies from metal to metal. Stainless steel does not form thick oxide layers but the attractive bond between the metal and oxygen is very strong. Copper oxidizes more than stainless steel but only forms weak oxide bonds. The bond between tin and oxygen is especially weak. Nickel oxidizes very slowly but the bond with oxygen is fairly strong –less than the bond between stainless steel and oxygen but far greater than the force with which oxygen bonds to tin or copper. Contrary to popular belief, not all shiny silver surfaces are easily deoxidized. Deoxidizing chromium, a shiny silver metal, requires very strong acid.

The difficulty of deoxidizing a part (i.e., required acidity) is determined by the type of metal and the thickness of the oxide layer. Lightly oxidized copper can be deoxidized by a weaker flux than needed to deoxidize the same copper with thicker oxide. Deoxidation of lightly oxidized stainless steel always requires stronger flux than required to deoxidize even heavily oxidized copper. The greater difficulty of removing thicker oxide layers results from two factors:

1. Oxides are basic. The reaction with oxide neutralizes flux acid. (The chemical reaction produces water and metal salts.) The acid content may be exhausted before all oxides are removed. And
2. Even if the acid is not exhausted, oxides under the surface oxides cannot be removed until the surface oxidation has been removed before application of the solder.<sup>7</sup>

5. More accurately, since atmospheric oxygen atoms normally travel in pairs (O<sub>2</sub>), the oxide’s pores would need to be larger than an oxygen pair.

6. Further, unlike stainless steel oxide, rust tends to flake off and expose the underlying iron.

7. Flux must work faster in hand soldering than surface mount reflow or wave soldering. With hand soldering, heat to activate the flux comes from the iron and the solder melts soon after application of the iron. In machine soldering, heat is applied for many minutes before the solder melts (or, in wave soldering, touches the area to be soldered). This long preheat means activated flux has a greater opportunity to remove thicker oxides.

## “SOLDERABLE” AND “SOLDERABILITY”

The concepts of solderability and solderable – two words that seem interchangeable but actually have very different meanings – are crucial to understanding soldering and fluxes. “Solderability” means the difficulty of removing oxide from a range of parts. Solderability is relative rather than a fixed condition. If Part A can be deoxidized more easily than Part B (that is, by a weaker flux), Part A has better solderability. Tin has better solderability than copper which has better solderability than nickel. However, among various pieces of the same metal, those less heavily oxidized will have better solderability than those with thicker oxide. Since the oxide layer typically grows over time, solderability of components typically degrades with age. Newer parts usually have better solderability than older parts with the same metal surfaces.

Although they may seem like synonyms (and are often confused) the meanings of “solderability” and “solderable” are very different and the difference is important. Solderable relates entirely to the flux being used. While solderability is comparative (Part A having better solderability than Part B above), solderable is binary (yes, it is solderable, or no, it is not) and has meaning only for the flux being used. If the flux to be used will deoxidize the part in the time available until application of solder, the part is solderable. If the flux being used cannot remove all the oxides in that time, the part is not solderable.

Better solderability does not necessarily mean solderable. The Part A that we specified as having better solderability than Part B can be solderable without the same being true for Part B. But Part B cannot be solderable if Part A is not solderable. And it is possible that neither part is solderable with the flux to be used.

## PREVENTION OF REOXIDATION

Flux is used to remove oxides. However, there is no point in removing oxides if new ones can form before solder application. And it must be remembered that an oxide-free metal surface exposed to oxygen (the air around us) will instantly be totally covered with oxide. The oxide layer may thicken with time but all the energy required for wetting is lost with the creation of that initial instantaneous oxide.

Sandpaper can remove oxides. (Plumbers sand pipes all the time.<sup>8</sup>) But oxygen can reach the newly exposed pure metal, so new oxides form instantly. The new oxide layer may be just a single molecule thick but that tiny layer has no surface energy and wetting will not occur. Just removing oxides is not enough. Formation of new oxides must be prevented.

**Flux can be defined as any material that removes oxides and prevents formation of new oxides until solder can be applied.**

Many materials can prevent reoxidation as well as removing initial oxides and some of those materials can be surprising. Hydrogen gas, for example, is used in soldering some small high frequency radio modules where even small amounts of flux residue would cause unacceptably high current leakage.<sup>9</sup>

8. Sanding pipes, which may have very thick oxide layers, removes the heaviest oxides and reduces the amount of work required from the flux.

9. The components (placed on solder preforms) are inserted in ovens filled with hydrogen and (inert) nitrogen gas. At roughly 660°F/350°C, the energized hydrogen strips the oxygen from oxide (forming water vapor). The modules emerge from the oven with thoroughly wetted solder connections and no flux residue.

## FLUX INGREDIENTS

Setting aside exotic but rarely used materials like hydrogen or formic acid/nitrogen gas, all electronics-grade fluxes contain:

**1. Acids** (which the industry, for reasons long forgotten, insists on calling “activators”) to remove oxides. Acids in electronics-grade fluxes are usually quite mild. Lemon juice is more potent than the acids found in high reliability fluxes. Although extremely strong fluxes used for purposes like plumbing are frequently called “acid fluxes,” that is sloppy terminology. All electronics fluxes contain acids, even if the acids are not very strong. Precision in terminology is important.

**2. Coating material** (“solids” also known as “vehicles” or, if you want to impress with fancy words, “rheological additives”) to prevent oxygen from reaching the deoxidized surface. Traditionally, the solids consisted of rosin derived from pine trees sap, but resins are common and a widely used class of fluxes known as “organic (OR) fluxes” often but not universally have glycol or glycerin as solids. Rosin is not soluble in water, but glycol and glycerin are. Some resins are water soluble, others are not.

**3. Solvent** (if liquid flux). Isopropyl alcohol (IPA) is the most common solvent but water-based fluxes exist,<sup>10</sup> used primarily in areas with serious smog problems.<sup>11, 12</sup> The sole purpose of solvents is easy application of the materials (acid and solids) that do the actual work.

## ACIDS

The part of the flux that removes oxides is almost always acid, either directly or in a compound that releases acid when heated. The term used to describe flux acidity is “activity.” Most often, the acids are organic (meaning they contain carbon). Inorganic acids (compounds of hydrogen with non-metals) such as hydrochloric or hydrobromic have exceptional oxide removal properties but are not compatible with electronic reliability; they leave highly conductive and corrosive residues that can cause electrical failures. Inorganic acids in the form of halides (discussed below) are found in some electronics fluxes but in very low concentrations and only supplemental to the greater amounts of organic acid.

Acid strength is determined by its hydrogen ion content; more hydrogen ions equate to greater acidity. During deoxidation (the interaction of the acid with the metal oxide, a base), hydrogen from the acid combines with the oxygen stripped from the oxide to form water while the other elements of the acid combine with the metal to form metallic salts. Stronger acids, in general, attract oxygen with more force than weaker acids. The greater attraction means stronger acids have greater deoxidizing ability (able to remove greater amounts of oxide faster than weaker acids and able to remove oxides from a greater range of metals than weaker acids).

10. Deoxidation is an endothermic chemical reaction, meaning the reaction requires heat and happens faster at higher temperatures that are not reached until after complete evaporation of the solvents. Evaporation of alcohol uses little energy, but evaporation of water requires considerable energy. Consequently, alcohols are preferred to water for solvents.

11. VOCs combine with nitrogen oxides to produce ozone, a major ingredient in urban smog.

12. There is a difference between water-based and water soluble. The residues of alcohol-based fluxes may be soluble in water. This is an important consideration in post-solder cleaning.



## Strong And Weak Acids

Let's pause to offer chemists an apology for the use here of the words "strong" and "weak" in referring to acidity. For our purposes, we can think of "strong" acids simply being more powerful than "weak" acids. But chemists don't mean potency when classifying acids as strong or weak. To them, strong acids are those that break into their constituent parts ("ionize") when added to water. Weak acids do not ionize completely while strong acids do. This special terminology causes considerable confusion for non-chemists when laboratories testing cleanliness of circuit assemblies report that failures are due to excessive amounts of weak acid residues.

### It's Mostly About Hydrogen

The "strength" of an acid depends on concentration of hydrogen ions. A lower concentration (content by total volume) of acid will have lower pH or acid number than a higher concentration of the same acid. This is important with respect to use of very reactive halides in electronics fluxes, discussed below.

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Aqueous solutions contain hydrogen in two forms: hydrogen ions  $[H^+]$  and hydronium ions  $[H_3O^+]$ . A hydrogen atom (H) consists of one proton and one electron. The hydrogen ion ( $H^+$ ) has no electron and is just a proton (in fact, chemists often refer to  $H^+$  as a proton rather than hydrogen ion). Hydrogen ions are highly reactive and can be donors of protons or recipients of electrons in chemical reactions.

Solutions containing more  $H^+$  than  $H_3O^+$  are acids. Solutions with fewer relative hydrogen ions are basic. The  $H^+$  concentration is expressed as pH, the negative log of the hydrogen ions per liter –  $pH = -\log_{10}[H^+]$  where  $[H^+]$  represents the hydrogen ion concentration in moles (M).<sup>14</sup> The pH scale runs from 0 to 14 with 7.0 being neutral,<sup>15,16</sup> Numbers smaller than 7 (higher concentrations of  $H^+$ ) are acidic and greater than 7.0 are basic.

This is a highly simplified look at acids. There are actually three different definitions for acid, two of which are exclusively concerned with hydrogen but a third defines acid in a manner that does not require hydrogen. It's not necessary for our purposes to go there.

### pH vs. Acid Number

Non-chemists often think of acid strength in terms of pH but, for the most part, pH is not relevant where flux is concerned. The solvent of most liquid fluxes is alcohol rather than water while pH applies only to water-based solutions. For solutions not based on water, the relevant measure of strength is "acid number," the number of milligrams of potassium hydroxide (a base) required to neutralize a gram of the acidic material. Acids work the same in aqueous and non-aqueous solutions; only the acid measurement system differs.

13. The hydrogen ions  $H^+$  are actually paired with oxygen in the form  $OH^-$ , known as hydroxide, but the hydrogen behaves like a standalone ion and chemists refer to the hydroxide as hydrogen ions.

14. M represents moles per liter of water where 1 mole = 602,214,076,000,000,000,000

15. A liter of pure water at 25°C contains  $1 \times 10^{-7}$  M hydrogen ions and the same number of hydronium ions.  
 $(1 \times 10^{-7} \text{ M}) \times (-\log_{10}) = 7$

16. "Neutral" is actually a moving target that depends on temperature. Neutral water at 25°C has pH of 7.0. At 0°C, neutral pH is 7.4 while neutral pH at 50°C is 6.63.

## “Neutral pH” Flux

Most flux companies sell fluxes labeled “neutral pH.” And they are extremely effective for oxide removal, capable of deoxidizing some of the least solderable metals. How can something “neutral” (which, after all, means non-reactive) remove oxides? The answer, of course, is that they are not “neutral” at all temperatures

Neutral fluxes come in two forms. The first goes on as a neutral compound but produces acids when heated. The acids are very strong and, therefore, excellent for deoxidation. But the highly conductive and corrosive ionic residues that result must be removed after soldering.

The second type starts out with high acidity but is neutralized by reaction with oxygen at high temperatures, typically 150°C or (often much) more. These conditions cannot be guaranteed (and are, in most cases, unrealistic). Not all of the flux reaches the neutralization temperature and any flux in cavities or under components displaces the air (and oxygen) needed for neutralization.

Both types of neutral flux come with the requirement that they be washed off after soldering. The residues are water soluble and can be removed by water – if the water can reach the residues. This is not certain. Flux has low surface tension that allows it to penetrate tight spaces. In fact, the ability of the flux to enter those spaces that require deoxidation is very important. But water has very high surface tension and cannot reach flux in cavities. Moreover, tap water, like flux, contains conductive and potentially corrosive ions that will degrade reliability. Cleaning must use water from which the ions have been removed (“deionized” water). But the surface tension of deionized water is greater than the surface tension of tap water, increasing the likelihood that the wash water will not reach all flux residues.

## Activation

Deoxidation is an endothermic chemical reaction and happens faster at higher temperatures. Although some strong acids can remove some oxides at room temperature, all acids work faster when heated. The acids in high reliability electronics fluxes generally do not begin to work at all until heated. The minimum temperature at which the acid begins working is the “activation temperature.” The activation temperature is often in the range of 150°F/65°C but that is only the starting point.

In many cases, the flux acids begin as inert compounds at room temperature. They must be heated to break down and form acids.

## A Few Words About Halides

Although fluxes rely primarily on acids for oxide removal, some also contain small amounts of metal halide<sup>17</sup> to reinforce the acid. Only compounds of chlorine and bromine are used in flux but there are several possibilities and there is no way of knowing which halide is in a flux.

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17. Halides are compounds of metals and halogens such as chlorine, fluorine or bromine. Sodium chloride (table salt) is a common halide, though not one found in flux.

When the halide encounters water (one of the byproducts of deoxidation when hydrogen of the acid combines with oxygen from the oxide), it separates into the metal ion and halogen anion, generally either chloride or bromide. Interestingly, the halogen, like oxide, is a base, not an acid, but it vigorously attacks oxide. Why and how? The answer isn't clear. Scientists are still arguing about the reason halogens are useful in removal of metal oxide (possibly because the halogen is a stronger base than the oxide, but that has not been proven).

While the reason may be unclear, it is known that a small amount of halogen (from decomposition of the halide) enhances the work of the flux acids. It's also known that halogens carry a strong electrical charge that is destructive to electronic circuitry in large amounts. To qualify as halide-free under J-STD-004B, the flux classification system most commonly used by the electronics assembly industry, a flux must contain less than 0.05% halide by volume (meaning volume excluding solvent in the case of for liquid flux). That is a very difficult level to stay under and most fluxes suitable for use in production of reliable products do not qualify for halide-free status. However, high reliability fluxes contain less than 0.5% halide by volume. More discussion is in "Flux Strength Classifications" below,

## The Ionic Contamination Problem

In an ideal world, there would be no negative consequences for using the strong acids and halides that make deoxidation easy. Our world is not ideal, however, and both the acid and halides pose serious reliability challenges. The acid and halide residues are ionic or anionic (electrically charged atoms) and their residues after soldering are called "ionic contamination." Ions are electrical conductors and, potentially, corrosive. In general, though not absolutely, both conductivity and corrosivity increase with strength of the acid or base.

Conductive residues can allow electrical current to flow between non-common conductors ("current leakage") rather than through the circuitry. While most electronics assemblies can tolerate some current leakage, all assemblies have limits easily exceeded by the ionic or anionic residues of even relatively mild fluxes. Higher ionic levels (greater ionic charge and/or more ionic material) can allow formation of dendrites. And even higher ionic levels can cause corrosion.

The risk of ionic contamination failure is determined by flux acidity (greater acidity means higher risk) but also by humidity. Risks of serious current leakage, dendrites and corrosion increase with humidity. Assemblies that function perfectly well outdoors in Arizona (close to zero humidity) may suffer high failure rates in Miami (very high humidity) in summer despite having identical ionic contamination.

Choosing the appropriate flux acidity is a balancing act. Too strong (which, in terms of acidity, is rather mild where electronics are concerned) can result in failures from surface insulation (SIR) breakdown or, worse, corrosion. Weaker than the product can tolerate limits the range of solderable parts with no additional reliability benefit. The "goldilocks" choice is the strongest flux that will not cause ionic contamination failures. The right choice for some types of electronics can be wrong for others; the only way to know is by rigorous environmental stress testing.

## POST-SOLDER CLEANING

But why not just remove the flux after soldering? Wouldn't post-solder cleaning allow safe use of very strong acids? That would indeed be the case – if complete removal could be achieved. But it can't. Or, more accurately, there is no way to be sure that it can.

After soldering, remnants of two flux components remain: solids and acids. The residues of solids, especially rosin and some resins, can be easily seen but have little to no effect on reliability. Rosin, being impervious to moisture, actually helps reliability by acting like a conformal coating.<sup>18</sup> The acid residues (which are ionic – conductive and potentially corrosive), on the other hand, are not visible. An assembly with serious ionic contamination can appear perfectly clean. An assembly with visible rosin residues, on the other hand, may have perfect reliability even in high humidity environments.

In other words, in the world of electronics, “clean” is not a cosmetic condition. What can be seen is probably not a reliability problem. What can't be seen may be catastrophic. How “clean” is “clean” has been a contentious question for decades.

The nature of materials to be removed can also complicate matters. Rosin is not soluble in water (a polar solvent) but the ionic residues are only soluble in polar solvents such as water. Both solids and ionics of another class of fluxes (so-called “organic acid” fluxes) are soluble in water but not in non-polar solvents like alcohol.

The materials to be removed may be soluble in the cleaning solvent but only if the solvent reaches them. Modern electronics assemblies with surface mount component bodies almost touching the PCB make complete contact between cleaning solvent and contaminants almost impossible. The issue is relative surface tensions of flux and cleaning solvents. Alcohol-based fluxes (the most common type) have very low surface tension and penetrate small gaps and capillaries. They readily flow under low-lying surface mount components. But removal of ionics requires use of polar solvents, the most common being water. The surface tension of water is much higher than that of alcohol (flux), however, which prevents penetration of cavities.

Further complicating matters, tap water itself contains ions that will themselves contaminate circuitry. Removing ions from water (“deionized water”) causes surface tension to increase. Surfactants are often added to reduce the surface tension of water wash but the effect leaves the solution with higher surface tension than the flux. Spraying, ultrasonic vibration and other hydraulic forces are applied to force cleaning solution into the tight spaces, but there is no way to determine whether the result is adequate removal of all flux residues. Quite simply, there is no way to ensure that cleaning results in acceptable cleanliness. Ionic matter concentrated in a small area of conductors like component leads can be enough to cause failure even though the rest of the circuitry is totally free of ionic residues.

Cleaning not only does not guarantee reliability, it is expensive. Cleaning can be more expensive than the soldering itself. We will return to this issue a bit later.

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18. Rosin residues do negatively affect adhesion of some actual conformal coating, can contaminate test probes, and is sticky until curing. Modern “no clean” rosin fluxes leave very little residue, however.

If cleaning is expensive and not foolproof, why bother cleaning? Using flux that can be left on the assembly with no degradation of reliability is cheaper and more reliable. “No clean” fluxes exist and are ideal in most electronics assembly applications. But, as we will discuss again later, just because the label calls the flux “no clean” does not guarantee that it is truly safe.

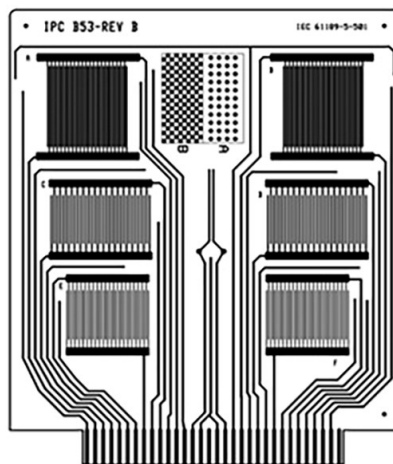
## FLUX STRENGTH CLASSIFICATIONS

Electronics fluxes are classified as low, medium or high “activity”<sup>19</sup> (written L, M and H) on the basis of the conductivity and corrosivity of their residues after soldering. The rules are spelled out in an industry document J-STD-004B issued by the trade association IPC.

Corrosivity is determined by applying the flux to a thin layer of copper on a glass plate and seeing whether and by how much the flux breaks through the copper, leaving only the glass. (Where copper has been removed, it is possible to see through the glass underlay.) Conductivity is more complicated.

The procedure for determining conductivity is rather complicated but, in essence, the steps are:

1. Apply the test flux (from cored wire solder, paste, liquid or solder paste) to coupons (laminated with a comb pattern of fine traces spaced .020” or .508mm apart).
2. Run the coupons through a reflow oven set to normal process temperature or across a solder wave..
3. Clean some of the processed coupons.
4. Place the clean and uncleaned coupons in an environmental chamber at 40°C and 90% relative humidity.
5. Apply current and measure the change in SIR after 96 hours and after 7 days



Conductivity test coupon with comb pattern

19. And “activity”, of course, means acidity

Flux passes the test if:

- a. The SIR does not fall below 100 MΩ at any point and
- b. The SIR does not fall below 1000 MΩ after 96 hours until conclusion of the test and
- c. Dendrites (electrical bridges between uncommon conductors created by migration of positively charged metal ions migrating to negatively charged conductor) do not form

Fluxes whose coupons pass the conductivity test without being cleaned and do not break through any coverage area in the copper mirror test are classified as low activity (L).

Some medium activity (M) fluxes that break through up to 50% of the coverage area on the copper mirror may pass the conductivity test without cleaning, but require cleaning to meet the conductivity limits.

H fluxes break through more than 50% of the copper mirror coverage area and require cleaning to pass the conductivity test.

Fluxes that cannot pass the conductivity test are stronger than H and not suited for use on electronics assemblies.

## The Flaw in J-STD-004B

The conductivity test has several critical flaws. Most importantly, heating the flux in a reflow oven or wave solder system can neutralize organic acids. With enough temperature (150°C or more) in the presence of oxygen (the air that surrounds us), the organic acids will oxidize and become neutral. In other words, the flux acids may be neutralized before conductivity and dendrite tests are conducted. Defenders of the classification procedure contend that the flux will exceed the neutralization temperature during production soldering. Critics (myself included) point out that this is by no means guaranteed. Flux that is not in contact with a soldering iron, for example, may never get above room temperature. Flux trapped in cavities or under surface mount components displaces the oxygen-containing air and will not oxidize no matter what temperature they experience. There are other scenarios under which flux fails to reach neutralization temperature. Further muddying the water, a group of fluxes use compounds that are initially neutral but form very strong acids when reaching a sufficiently high temperature that may be more than the peak temperature during processing of the test samples.

When selecting flux, the J-STD-004B rating is a good place to start; it saves a lot of time that might otherwise be spent evaluating completely unsuitable fluxes. However, the safety of the flux in its pure state (not heated) must also be taken into account. Many fluxes qualified as low activity by J-STD-004B have suspiciously high acid numbers and not all of that flux in every area of a circuit assembly will experience sufficient heating during soldering. Unfortunately, the information about flux conductivity before heating is not usually available.

Conductivity of flux residues does matter enormously. Failures occur when too much electricity chooses to flow through the acid residues between non-common conductors rather than following the circuitry.

How much current leakage is “too much” depends on the required precision of the product involved and the environment where the product needs to operate. (The problems with ionic contamination increase as humidity increases. An assembly sitting in a desert will be much less affected by ionic contamination than the same assembly in a swamp.).

## Some More About Halides

Halides get special treatment in flux classification. Because halide residues are highly conductivity and corrosive, fluxes containing halides are classified separately from those that do not (“halide-free”). And the amount of halide factors into the flux classification.

Only fluxes containing less than 0.05% halide by volume (based on the flux contents without solvent) can be classified as halide-free. Low activity halide fluxes contain less than 0.5% halide by volume. Medium activity halide fluxes are limited to less than 2.0% halide content while fluxes containing 2% or more halide are all classified as H. This results in six activity levels: L0, L1, M0, M1, H0 and H1 where 0 represents halide-free and 1 designates those containing halides within the specified limits.

## SOLIDS

Oxides must be removed or the solder will not wet. However, removal of oxides, on its own, is not sufficient. If oxygen can reach the deoxidized surface, new oxides will form instantly and the surface energy lost. In addition to removing oxides, flux must provide a barrier preventing oxygen from reaching the newly deoxidized metal until solder is applied. That is where the solids come in.

Flux manufacturers have their own jargon, such as “activators” instead of acids. The traditional but increasingly uncommon jargon for solids is “vehicle,” presumably because the acids are carried in the solids. “Solids” more accurately reflects the material’s role in providing the barrier against oxygen.

## The Role of Solids

Solids exist only to prevent oxygen from reaching the deoxidized metal while solder is being applied. That’s their entire function.<sup>20</sup> They do not remove oxides. They are not conductive. They are not corrosive.

Solids make up a much greater percentage of the flux volume than the acids and their remnants (if any) are what can be seen after soldering; the acids are not visible, so a visibly “clean” circuit assembly may be an ionic disaster. As contract manufacturers know, however, their customers have no knowledge of soldering science and, believing visible flux residues must be evidence of reliability issues, want to reject assemblies when residues can be seen. (Depending on the type and quantity of solids, they can cause problems such as contaminating test fixture pins or preventing proper adhesion of conformal coating, but these do not in themselves affect product integrity. In the case of conformal coating, switching coating materials can often eliminate the adhesion problem.) Because of pressure from uninformed customers, many contract manufacturers adopted flux formulations that leave no visible residues and, of course, flux manufacturers created new formulations to meet demand for invisible solids.

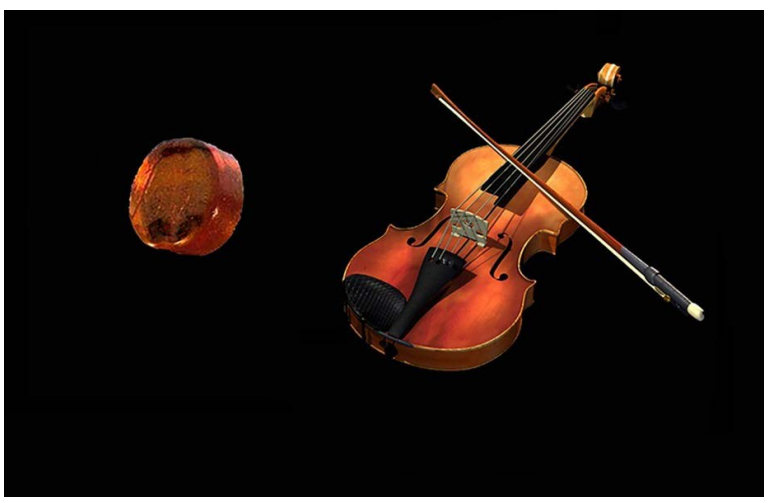
20. In the days before surface mount parts on both sides of printed circuit boards, high concentrations of rosin were useful for prevention of bridging during wave soldering. With the arrival of bottom-side surface mount components, concentrated rosin, rather than beneficial, became a contaminating barrier preventing consistent contact between solder and components.



## Rosin

Historically, all electronics fluxes used rosin<sup>21</sup> for solids. Rosin is derived from sap of certain pine trees after most of the volatile components have been evaporated (forming turpentine, among other derivatives). Anyone who has handled a Christmas tree is very familiar with one rosin property – it is very sticky (until all remaining volatiles evaporate, at which point the rosin feels and acts very much like polyurethane, although the two materials are very different chemically).

Rosin has two properties that make it ideal for use in electronics fluxes. First, it tolerates soldering temperatures without breaking down, ensuring that the deoxidized surface remains protected from oxygen. Second, and even more important, it is hydrophobic (repels moisture). Rosin encapsulates the acids in a moisture-free environment that minimizes conductivity and corrosion. (All the unpleasant consequences of ionic contamination require some humidity. Resistance to current leakage goes down as humidity increases.)



The disc is the same rosin used in flux.  
Musicians use it with stringed instruments.

Rosin in its natural state contains a very mild organic acid, abietic. The acid is not strong enough to remove many oxides other than tin oxide. Stronger acids are added to fluxes suitable for production but rosin in alcohol without extra acids is still sold for use with tin-plated parts. (Under the now obsolete MIL standard for flux, rosin in alcohol is designated “Type R.”)

Rosin is nonpolar, so not soluble in water, which is polar.<sup>22</sup> Attempting to mix rosin in water results in a gooey mess (not a technical term but an accurate description). Powerful solvents such as trichloroethane that were very effective for removing rosin residues in the past are now banned for environmental and health issues. No currently available solvents can equal the ability of trichloroethane and its close relatives to remove rosin. Moreover, the solvents that are available today are expensive. Rosin is intended to be left on the circuitry after soldering.

21. The technical term for rosin is colophony.

22. Solvents are either polar (their molecules point in the same direction) or nonpolar (molecules are randomly positioned). Water is polar, alcohol is not. Ions dissolve in polar solvents but not in nonpolar. Rosin, oils and many other materials do not dissolve in polar solvents. Cleaning of rosin flux involves removal of both the rosin (nonpolar) and acid residues (polar), a rather challenging proposition.



The main issue with rosin is its visibility. The brown residue stands out after soldering. The residue is harmless<sup>23</sup> but too often interpreted by the uninformed as signifying poor reliability. Soldering operators often spend great time and effort removing the visible rosin after soldering, a total waste of resources. "Cleaning" with a brush or cloth and solvent after hand soldering accomplishes little except spreading the flux residues over a larger area and reducing visibility; there is no meaningful effect on reliability.

The amount of residue remaining after soldering is determined by the concentration of solids in the flux. The way to avoid annoying amounts of rosin residue is to avoid fluxes with high concentrations of rosin. Because they were formulated for early versions of wave soldering where excess solder such as bridges could be prevented by high concentrations of rosin (40% or more in some cases), many rosin fluxes still in common use today contain many times more solids than are needed or desirable for today's soldering.<sup>24</sup> Dark brown liquid flux provides no benefits to compensate for the time and money required to remove the residues after soldering. Most flux manufacturers today offer low solids (less than 5% by volume) liquid rosin fluxes that leave no meaningful residue



These fluxes are identical except for rosin concentration but the flux on the left requires no cleaning after soldering

Flux cored wire solder leaves residues. The default flux content of wire solder is around 3% by weight, which translates into a very large quantity by volume. Using solder with around 1% flux content eliminates the major source of visible rosin residue. The flux inside the solder provides no great benefit in any case.<sup>25</sup>

23. The acid contained in the rosin may be an issue, but that is independent of the rosin itself.

24. As noted earlier, concentrated rosin was useful decades ago in wave soldering but is counterproductive today.

These fluxes are identical except for rosin concentration but the flux on the left requires no cleaning after soldering

25. Soldering requires the application of liquid flux even though many "experts" claim that it is possible to solder with only flux-cored solder. Cored solder was developed in an era when all component leads were plated with tin or tin/lead. The plating melted when solder was applied and oxides – being lighter than pure metal – would float on the liquid metal. Flux, also lighter than metal, from the solder also floated. The flux did little more than clean up the surface to make the connection more attractive. That is not true of soldering, the process in which surfaces being soldered do not melt. Most of the surfaces being soldered today do not melt and this requires the use of liquid flux.

## Resin

The disadvantage of rosin solids for flux manufacturers involves profits. Rosin is rosin, regardless of the flux manufacturer's label. At a fundamental level, there is no meaningful difference between one brand of rosin flux and another in the same activity category. But substituting a material other than rosin for the solids allows for product differentiation – and the potential for somewhat higher pricing and profits.

One type of material used in place of rosin is resins. And this gets tricky.

The Cambridge Dictionary defines resin as “a thick, sticky substance that is produced by some trees and that becomes yellow and hard after it is collected, or any of various similar substances produced by a chemical process for use in industry.” We have already discussed the material in the first part of that definition: rosin. And some resins refined from rosin do have properties very similar to rosin. But other resins are not related to rosin; they are the results of chemical synthesis. Rosin is rosin but resins have many forms and, since no manufacturer reveals their proprietary ingredients, there is no way of knowing the resin used in any particular resin flux.

## Water Soluble Solids (Organic Flux)

As noted previously, customers of contract manufacturers (or internal customers of integrated companies with in-house production) often reject assemblies with visible flux residues. The easiest way to placate uninformed customers is to replace visible solids (rosin or some resins) with colorless solids. Glycols and glycerins are among the most popular replacements.

Glycol and the more viscous glycerins are colorless and water soluble. They leave very little visible residue after soldering and, unlike rosin, can be removed by water wash if necessary. The lack of visibility and ability to be removed by water (as opposed to expensive chemicals needed for removal of rosin) makes these fluxes very popular with contract manufacturers as well as companies producing for their own use but lacking enough knowledge to understand why rosin residues do not in themselves mean poor reliability (or that lack of visible residues in the case of solids like glycols do not necessarily reflect high reliability).

## SOLVENTS

Fluxes are available inside wire solder, mixed with solder particles in solder paste, as gels or pastes and as liquids. The feature that distinguishes liquid flux from the other forms is solvent.

The most common solvent is an alcohol. It doesn't really matter what alcohol is used; they all behave similarly. Two characteristics make alcohol the ideal flux solvent:

1. Low surface tension, allowing the flux to penetrate tight spaces where oxide removal may be required, and
2. High vapor pressure (the force that changes liquid to vapor without heat) that results in quick drying of the alcohol without using heat required to activate the flux and melt the solder.

Alcohols are volatile organic compounds (VOCs) that are possibly carcinogenic, contribute to smog, and act as greenhouse gases. VOC restrictions in some regions, most notably portions of California, prevent the use of alcohol-based flux. However, the alternative to alcohol is water, which is inferior to alcohol in four main ways:

1. High surface tension, so poor penetration of tight spaces including up plated through-holes
2. Very low vapor pressure, so little tendency to evaporate after application
3. Very high latent heat of vaporization. Driving off the water requires heating to 212°F/100°C, using energy that would otherwise help in activating the flux and melting the solder, and
4. Spattering when a hot iron touches the fluxed workpiece or a fluxed assembly enters a solder wave

Water based is not the same as water soluble. Water soluble means the flux residues after vaporization of the solvent are soluble in water. The residues of many alcohol-based fluxes (excluding fluxes containing rosin and some resins) are water soluble.

## FLUX CATEGORIES (MORE ABOUT J-STD-004B)

From the early 1960s until 1995, fluxes were classified by the US Department of Defense in cooperation with Bell Laboratories. The Department of Defense standard was MIL-F-14256. Qualification was based on corrosion, conductivity and miscellaneous concerns such as presence of halogens similar to those discussed in “A Few Words About Halides” earlier. The emphasis was on rosin-based fluxes of which three were defined: Type R (rosin in alcohol), Type RMA (rosin in alcohol with some stronger acid) and Type RA (RMA plus stronger acid). Anything stronger than RA was generally referred to (though not in the standard) as “superactivated rosin” or SRA. There were also specifications for water soluble fluxes and, in later revisions, Type LR (low residue). MIL-F-14256 itself was almost unknown outside the defense community although most commercial electronics manufacturers were aware of the three rosin categories.

Qualification requirements for rosin fluxes were well defined by MIL-F-14256. This meant that an RMA flux, for example, from one supplier would perform almost identically to RMA flux from every other supplier. In other words, rosin flux was a commodity with very low profit margins. Fluxes that used other solids were not so well defined and, with clever marketing, could often command premium pricing. Outside defense contracting, picking a flux meant figuring out the actual properties of mystery concoctions.<sup>26</sup> This changed with the introduction of a general industry classification system – J-STD-004 – in 1995.

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26. All flux manufacturers have their own proprietary recipes that they guard the way Coke famously hides its formula. Aside from a few generic ingredients such as rosin or isopropyl alcohol, most of the key additives are kept secret. The safety data sheet of one flux manufacturer states “Trade Secret exemption is pending with the [Hazardous Materials Information Review Commission] for one or more ingredients in this product.”

J-STD-004 replaced the MIL-F-14256 classifications. Fluxes were now categorized as RO, RE, OR and IN. The first two groups, RO and RE, are named after their solids. RO fluxes have rosin solids while RE contains resins. The last two are grouped by their acid types, organic (OR) and inorganic (IN). OR and IN<sup>27</sup> fluxes are water soluble.

Each category is then divided into low (L), medium (M) and high (H) activity. And each of the divided categories is further subdivided into halogen-free (0) or containing halogen (1). The result is a table with 24 cells:

ROL0	ROL1	ROM0	ROM1	ROH0	ROH1
REL0	REL1	REM0	REM1	REH0	REH1
ORL0	ORL1	ORM0	ORM1	ORH0	ORH1
INL0	INL1	INM0	INM1	INH0	INH1

The halide content limit for fluxes that are not halide-free increases from L to M to H. L1 fluxes must contain less than 0.5% halide by volume. H1 fluxes contain more than 2.0% halide. Any halide content in between is M1.

Logic might suggest that L fluxes would be comparable in strength to the former Type R, M to RMA and H to RA. But there is no direct correlation. All Type R fluxes will meet the requirements for ROL0 but most RMA fluxes qualify as ROL0 or ROL1. Occasionally but rarely, a flux that was marginally classified as RMA becomes an ROM0. RA fluxes are ROM1. All H fluxes are more conductive and/or corrosive than RA.

Nominally, all fluxes having the same last two designators (L0 or M1, as examples) should be roughly equivalent regardless of their solids. That is not true and this is where flux selection requires avoiding some hidden traps. Earlier, I noted that tests for conductivity begin after the flux has been heated by passing a fluxed circuit coupon through a surface mount reflow oven or wave solder preheat and, in the case of OR fluxes, this can affect qualification test results. Organic acids are sensitive to heat; in the presence of oxygen, they oxidize and become neutral when heated. The temperature which neutralizes OR flux is below peak surface mount reflow or wave solder preheat temperatures and this has led to the mistaken conclusion that all flux will therefore reach the neutralization temperature in the presence of oxygen. In actual production, especially with hand soldering, not all flux will reach the neutralization temperature. The conductivity test is based on best case outcomes rather than worst case.

Rosin fluxes behave differently than OR fluxes. Acids contained in the rosin will not be exposed to oxygen and cannot be neutralized by heat. At the same time, however, the rosin forms a moisture barrier that acts like conformal coating and reduces the possibility of failures from ionic contamination. Residues of OR flux solids do not provide the moisture barrier protection and, of even greater concern, tend to attract humidity.

Additionally, some OR fluxes produce white or brownish residues after soldering.

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27. Inorganic fluxes are very powerful and not generally suited to electronics applications.

## No Clean Flux

Removing flux residues is expensive. Among the costs:

- Cleaning solvents are expensive
- Cleaning equipment involves capital expenditures both for machinery and floor space as well as operating costs such as electricity
- Total production time increases
- Time spent cleaning is time not spent on production, often the greatest cost of all.

Even worse, cleaning cannot be guaranteed to remove all flux residues. The surface tension of most cleaning solvents is greater than the surface tension of flux, so flux gets into spaces like vias and under surface mount component bodies where cleaning can't reach. Even if the wash solvent can touch trapped flux, capillary forces prevent the flux from being extracted. Hand "cleaning" with a solvent and brush only moves the flux around.

In addition, there is no way to measure cleanliness after soldering. Cleanliness testing depends on the same solvents used in washing. Cleanliness is determined by immersing the assembly in a tank containing deionized water and alcohol. Any ionics absorbed by the test solution from the circuit assembly will increase the solution's conductivity. Algorithms calculate the amount of sodium chloride required to achieve the measured increase in conductivity. That amount is then divided by the circuit assembly surface area to yield amount of sodium chloride per square cm (or other area). Comparing the result to tables of acceptable limits then determines whether the assembly is "clean" enough. Such testing simply wastes time and money because:

- The system can only measure the ionics that the test solvent reached. But flux gets trapped in cavities from which it can't be removed – or measured, and
- An assembly may be free of ionic contamination except for one area of concentrated ionics sufficient to cause failure. The test method only reports "average" cleanliness while reliability depends on local concentrations.

We can be certain that there will be flux residues that can't be removed or detected. Logically, therefore, we must only use flux that will not cause ionic contamination failures. In which case, there is very little reason to "clean" the assembly after soldering. If the flux residues will not cause problems, why spend resources on an activity that does not add reliability? In other words, use a "no-clean" flux and skip post-solder cleaning.

Most flux companies sell fluxes they term "no clean." All those products, having very low solids concentration, leave little to no visible residue after soldering. But, as we've discussed, aside from possibly interfering with other process steps such as conformal coating, absence of visible solids should not determine whether the flux is safe without cleaning. The property that matters is acidity: will the result be free of current leakage, dendrites or corrosion? Not all fluxes bearing "no clean" labels are actually safe in ionic terms.

## CHOOSING THE BEST FLUX

So, what flux is best for you? It's not a case of one size fits all. Fluxes ideal for certain products and operating conditions may cause avoidable work or assembly failures when used for other products.

Here are a few general rules that prevent bad choices:

1. Use only fluxes that have been qualified using the J-STD-004B criteria. There is no way to know the potential conductivity and corrosivity of unqualified fluxes, but they are almost always stronger than electronics assemblies can tolerate. Bad things happen to companies that buy their flux at the hardware store.
2. If the flux (or any other material, for that matter) that you have been using has not caused failures, do not change without a very good reason.<sup>28</sup> Changing any material or process poses some risk; there needs to be a compelling cost or reliability reason for making any substantive change.<sup>29</sup>
3. If a new product is being introduced, however, there is no proven process and use of stronger fluxes requires thorough validation testing.
4. Always conduct thorough environmental and other performance tests before adopting flux with which you have no experience. Any changes to flux should also be documented.
5. Do not act on the basis of a supplier or consultant recommendations without having thorough understanding of the reason for the recommendation.<sup>30</sup> If the change doesn't work out, your company may be seriously injured and even bankrupt, conditions from which recovery can be very painful. Suppliers and consultants have less risk; if their recommendations don't work out, they can move along to other customers.<sup>31</sup>

More specifically:

1. Use the strongest flux that you can prove will not cause your product to fail in use if the flux is not removed after soldering. Using flux weaker than this increases the risk of solderability defects but stronger flux, by definition, will cause failures.
2. Do not believe that cleaning after soldering will remove all flux residues. It won't – and there is no way to prove that all flux residues have been removed. Therefore,

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28. Even if contracts require the use of fluxes other than what is being used successfully, long-term success with the existing flux demonstrates that the flux is acceptable. The existing flux is a "proven process" material and may continue being used. See, for example, Appendix C of J-STD-001H.
30. Not all customers will be familiar with the "proven process" acceptance provision, however. It may be necessary to push back. There may be times when it is easier just to make the material change than persuade the customer.
29. But be certain that field reliability is as good as you may think. Process engineers often do not have complete knowledge of warranty claims.
30. The same advice applies to the recommendations in this document.
31. Yes, some companies "clean" residues of no-clean fluxes. The usual result is reduced reliability despite increased cost. The solids residues of most no-clean fluxes encapsulate the acids.

3. Use a proven safe no-clean liquid flux – and do not clean. More than 5-6% rosin for liquid flux is excessive except for very specialized and rare applications. The higher the rosin concentration, the greater the need for cleaning after soldering. Most flux manufacturers offer very reliable no clean fluxes.
4. Rosin is better than Organic and preferable to Resin. Although a resin may perform as well as rosin, there is no way to know the nature of the resin used. I do not like using unknown materials.
5. High reliability applications like automotive, aerospace, telecom and medical should use low solids ROL0/ROL1/RMA flux. I have never seen a failure caused by this type of flux whether “cleaned” or not. Most defense contracts do not allow fluxes stronger than ROL1 (RMA) flux. It’s a sensible requirement.
6. M1 fluxes (excluding IN fluxes, which are not suitable for electronics no matter what their activity rating) should only be used to solder products such as office equipment that will be used only in low humidity environments and if occasional failures are tolerable (not a smart operating philosophy in general, but some companies are willing to accept some failures in exchange for manufacturing cost reductions). Even then, be very careful. But do not adopt anything stronger than L1 without conducting rigorous environmental testing of sample production.

The perfect no-clean flux is low solids ROL0 or ROL1. My default flux for several years has been AIM NC280, a low solids ROL1 flux that leaves safe ionic residues. Other manufacturers have similar formulations.

Never apply H or stronger fluxes to circuit assemblies. They are corrosive and cannot be completely removed. Even M fluxes should be used only with caution.

## A Final Note About Applicability

This document applies only to electronics assemblies. Some metals – brass and nitinol being extreme examples<sup>32</sup> – cannot be deoxidized by any flux remotely related to the world of electronics chemicals. Those items cannot be included in a circuit assembly without special treatment that I term “presoldering.” Using the high acidity flux that will remove the oxides, apply solder to the part then thoroughly remove the flux residues using the procedure in the next paragraph. The part can then be added to the assembly by reflowing the soldered surface using the standard production flux. Follow the same procedure for any components that are not solderable with the production flux. Most low solderability parts will not require battery acidity for deoxidation but still require pretreatment with very strong fluxes not suitable for circuit assemblies. All such fluxes will be water soluble.

Residues of the extremely strong fluxes must be removed before adding the part to the circuit assembly. Wash the part in deionized water (an ultrasonic bath is best) to remove the flux residues, then wash again in a second bath. The first deionized water bath will gradually become contaminated by ionics and must be replaced. What had been the second bath can be moved up to the first position and the original first cleaner (filled with fresh deionized water) moved to the second position. Repeat as necessary.

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32. Nitinol can only be deoxidized by concentrated battery acid. One company does sell nitinol- specific flux at a shockingly high price but battery acid does the same job for a fraction of the price.



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