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“The reasonable man adapts himself to the world; the unreasonable one persists in trying to adapt the world to himself. Therefore, all progress depends on the unreasonable man.”

— George Bernard Shaw
Preface

The opening chapters of this book will provide readers with numerous persuasive technical reasons to stimulate their thinking about SAFE manufacturing. This will be done by pointing out the many limitations and intrinsic problems of traditional manufacturing with solder and the potential technical and economic benefits which appear possible by making the change.

However, there are other prospective motivations to change with social and environmental implications.

Consider the following. Our planet is presently home to more than 7 billion people, and by 2020 that number will be close to 8 billion. However, the present global electronics industry has focused nearly all of its attention on the needs and wants of only the top 3.2 billion people. We are making products that are, for the most part, designed to be replaced by a future model. Some have suggested that we can take pride and comfort in thinking that we can service the needs of those born into less fortunate circumstances by reselling our old electronics to them at a steep discount. Unfortunately, those products are often nearing the end of their useful life. This does the second-hand user no particular good, however well-meaning our intentions.
With little disposable income, the world’s poorest people need the highest-reliability products.

Consider and answer the following question: “What do military, aerospace, automotive and medical product developers and users have in common with the world’s most economically challenged people?” The answer is that they need to have the most reliable electronics that can be possibly made. In the former case, it is because they need to have products that will work flawlessly for the expected performance life to meet mission or application needs. In the latter case, it is because an individual making less than $2 a day simply cannot afford failure due to economic limitations. For those fortunate-born members at the top of the pyramid who find ourselves economically privileged, when a product fails we simply buy another one. This is out of the question for the poorest of the poor.

All on the planet will benefit in the long run by placing reliable, affordable tools for communication, education and personal growth (phones, computers, etc.) in the hands of those whom fate has dealt a lesser and less playable hand. All that is required is for product developers to challenge themselves to “Think Different” when it comes to thinking about serving the needs of the world’s most disadvantaged.

— Joseph Fjelstad
January 2017
“It is vanity to do with more that which can be done with less.”

William of Occam
Introduction
(The Sisyphean Challenge of Solder)

As the title of this book declares, this text is about the manufacture of electronic assemblies without the use of solder. Its genesis began with the European Union’s RoHS legislation in 2006 banning the inclusion of lead (Pb) in solder used for electronics manufacturing. That legislation placed significant restrictions on a number of materials used in electronics manufacturing, but it is the banning of the use of lead in solder which has had the greatest impact on electronics manufacturing. Those rules have imparted significant challenges on the electronics industry since their introduction and the greatest impacts have been felt by the mandated elimination of lead from electronic solder concurrent with the demand for the elimination of halides from flame retardants used in traditional printed circuit board (PCB) laminates. In the years that followed, the electronics industry has been beset with a host of new challenges in its effort to comply.

To be certain, a substantial percentage of the process and reliability problems which have confronted the electronics manufacturing industry have related to solder assembly. Historically, the fundamental underlying cause is the high temperatures required to carry out the soldering process. Now these conditions have been made worse by the even higher temperatures associated with lead-free solder alloys. While lead-free solders were advertised early on as a drop-in replacement for traditional tin-lead solders, field experience proved this not to be the case.

Ten years later the industry is still struggling on a daily basis to make reliable cost-effective electronic products using lead-free solder. Pick up any journal or magazine on electronics manufacturing and it is likely to have most of its commentaries and articles focused on concerns or prospective solutions related to the soldering process. It remains a vexing and costly challenge but it is believed, and will be hopefully convincingly shown to the reader in this book, that solder is not necessarily required for the manufacture of electronic assemblies.
For the benefit of the reader in appreciating more fully the challenges presented by the soldering process as it stands today, consider Figure 1.1 and the following litany of concerns related to soldering with descriptions:

1. **Opens**: Opens are discontinuities generated in the soldering process. They can be manifested in assembly in a number of ways. For example, a bent or lifted lead on a QFP component, missing solder ball on a BGA, insufficient solder on an LGA, or the warpage of the component during the high-temperature lead-free reflow process can all result in an open circuit.

Figure 1.1: Solder defects are a major cause of electronic failure.
2. **Shorts**: Solder shorts are bridges of solder between one or more component leads on an assembly. As component lead pitch continues to drop the incidence of short circuits increases. Presently the “threshold of pain” for most assembly is experienced when the lead pitch drops below 0.5 mm.

3. **Insufficient solder**: Insufficient solder is a condition where the amount of solder in a solder joint is less than desired or specified contractually through industry specifications or customer requirements.

4. **Excessive solder**: Excessive solder is obviously the opposite of the condition of insufficiency and is again measured against agreements. It also introduces a wild card because it is not what reliability testing is based on.

5. **Solder cracking**: Solder cracking is an obvious concern as it could result in a latent open circuit condition. It’s good during product test before shipping but then failing in the field.

6. **Tin whiskers**: Tin whiskers are small metal projections emanating from a solder joint. They can grow in length up to 15 mm and, given the fine pitch of today’s components, they are a significant concern. They are also challenging because they are typically a latent defect that shows up unpredictably. Past research indicated that the addition of lead to tin solder alloys would mitigate the formation of whiskers, however with the ban on lead in electronic solders the incidence of whiskers is on the rise.

7. **Poor wetting/dewetting**: Good wetting is manifested by the presence of a uniform coat of solder on both the leads of the component and terminations of the printed circuit to which they are joined. In areas of poor wetting or dewetting, the solder thins appreciably in areas leaving only a thin, silvery sheen.

8. **Voids**: Voids are defects which are often difficult to detect without the use of special equipment such as an X-ray apparatus. The challenge with voids is that they represent potential weakness in the solder joint owing to their inconsistent nature. Voids can be found both in through-hole and surface mount components. In the case of surface mount components, the voids are often extremely small and are sometimes referred to as champagne voids.

9. **Blowhole**: Blowhole is a term applied to a phenomenon where a small hole is observed in a solder joint. Typically, the defect is found to be
the result of discontinuities in the plated through-hole wall which may absorb flux and then explosively outgas during the soldering process.

10. **Cold solder joints**: Cold solder joints are solder joints which did not completely form a good metallurgical bond. They are often the result of the joint receiving insufficient heat to cause complete melting and joining of the solder. Cold solder joints are often seen in cases where the component lead is connected to a large, thermally conductive feature or element and insufficient heat is retained near the lead to assure a good solder joint. With lead-free solders, the phenomenon provides a greater challenge as the amount of heat which must be applied is much greater than it might have been with a tin-lead solder, thus potentially degrading device and assembly reliability.

11. **Brittle solder joints**: Solder joints made brittle through the dissolution of other metals into them. Noble metals such as gold are used to help provide long-term solderability but even small amounts of included gold can reduce solder joint reliability.

12. **Head-on-pillow**: Head-on-pillow is a new type of defect which was manifested and identified only with the introduction of lead-free soldering. It is an unsettling type of defect in that it is not easily detected but could result in an intermittent open in the operation of the assembly. The term was chosen because the phenomenon is reminiscent of an individual’s head forming a depression on a pillow.

13. **Graping**: Graping is another lead-free related defect wherein the small, often ball-like particles of solder in a solder paste do not reflow completely, leaving a surface which looks like the surface of a bunch of grapes. Like head-on-pillow, it is a defect which may not be easily detected.

14. **Tombstoning**: A term used to describe a defect related to discrete devices such as resistors and capacitors, wherein solder connections are not made simultaneously and the component stands on end after soldering, resembling a gravestone.

15. **Component cracking**: Component cracking can have multiple causes, one being a situation where there is a significant mismatch in terms of coefficient of thermal expansion between the component and the printed circuit to which it is attached. It can also occur if the assembly is flexed in the area of the component, causing the device to crack.
16. **Popcorning**: Popcorning is a phenomenon manifested when moisture entrapped within a component outgases during assembly, causing a blister to form in the encapsulation material. With the advent of lead-free soldering and its higher temperatures, the incidence of popcorning also rose and, in fact, moisture sensitivity levels of components were increased for many devices to reflect the new reality.

17. **Solder balling**: Solder balling is a condition which happens during the reflow of a solder paste on a surface mount assembly. It is a result of the high temperature of reflow causing rapid volatilization of the flux and the accompanying spatter of the solder particles that are part of the flux. While a viable solder joint may be created even as solder balls are being formed, they represent a risk to the long-term reliability of the assembly as potential shorting elements.

18. **Misregistration**: Components with fine-pitch leads, if jostled before or during the assembly, may be misregistered relative to the land pattern, resulting in a nonfunctional product.

19. **Insufficient cleaning under devices**: As mentioned previously, insufficient cleaning under surface mount devices can result in latent failure through the formation of high-resistance shorts or the growth of dendrites.

Lead-free solder also had spillover effects on the PCB laminate material, a sort of unintended collateral damage. Presently there are a number of defects which can be generated within a printed circuit assembly because of the soldering process; these include:

1. **Corner cracking**: A crack which forms at the interface between the hole and the land which surrounds it. It is normally the result of the z-axis expansion of the printed circuit board during the thermal excursions such as soldering.

2. **Barrel cracking**: Barrel cracking is another phenomenon associated with the soldering process. It is similar in some ways to a corner crack except that it is manifested near the center of the hole. It is often associated with thermal cycling.

3. **Post separation**: Post separation is a separation of the plating in the through-hole from an innerlayer connection due to lateral thermal expansion of resin in the hole.
4. **Hole wall pull away**: Hole wall pull away is manifested as a bulge in a plated through-hole which reduces its diameter, making pin insertion difficult. It can also potentially break connections to internal lands on multilayer PCBs.

5. **Resin recession**: Resin recession is roughly the opposite of hole wall pull away wherein a small gap is formed between the plated hole wall and a resin-rich area of a plated through-hole. It is normally manifested after exposure to a high-temperature excursion such as soldering.

6. **Delamination**: Delamination is a separation of the layers of a multilayer circuit. It normally is seen in cases where the glass transition temperature of the resins used in the multilayer structure are exceeded.

7. **Pad cratering**: Pad cratering is another phenomenon unseen before the introduction of lead-free soldering. It is manifest as a circumferential tear in, and breaking, of the connection of the copper land to which a component, normally a BGA, is assembled.

8. **Decomposition**: Decomposition of a printed circuit board is a relatively new concern associated with higher temperatures used with lead-free soldering. The temperature of decomposition is defined by the loss of a specified percentage of the weight of the printed circuit. Before lead-free soldering it was a term rarely specified in laminate selection.

Examples of the most of the described defects can be seen in Figure 1.2.

![Figure 1.2: Examples of collateral damage to PCBs caused by the soldering process.](image)
Clearly, printed circuit technology, like soldering technology, is fraught with its own vulnerabilities due to the complexities of processing. There are a number of intrinsic challenges in just getting the board manufactured successfully, and many features and elements of a traditional PCB can degrade its electrical and electronics performance. These are illustrated in Figure 1.3.

Thus, in this challenging environment, an alternative approach to manufacturing electronic assemblies was conceived and is being promoted, experimented with and developed in locations around the globe. The alternative method in simplest form is one which eschews the use of solder for assembly.

The Occam process was inspired by the words of 13th century philosopher, monk and logician, William of Occam, who asserted to his followers that,
“It is vanity to do with more that which can be done with less.” The concept was as such originally promoted as the Occam process as an homage to Occam and the term *Occam process* is now universally identified with Verdant Electronics, which has licensed its patent portfolio to companies in Asia and the U.S. However, the technological opportunity is broader in scope than Occam and the term SAFE has been used alone and in combination with Occam as it encompasses a wider range of potential solutions than those described in Occam patents.

The result is an assembly which is created without using a soldering process, the process which is both the cause and effect of most electronic failures. Hopefully the balance of this book will allow the readers to convince themselves of the reasonableness of this approach for the benefit not only of their companies but for the benefit of their individual companies’ loyal customers.

Figure 1.4. Unfortunately, there are similarities between manufacturing PCBs with solder and the myth of Sisyphus who was condemned to push a boulder up the same hill every day for eternity.
“Perfection is achieved, not when there is nothing more to add, but when there is nothing left to take away.”

Antoine de Saint-Exupery

“Simplicity is the ultimate sophistication.”

Leonardo da Vinci

“Everything should be made as simple as possible but not simpler.”

Albert Einstein

“Simplify, simplify.”

Henry David Thoreau
CHAPTER 2
A Brief History of Solderless Interconnections

Solder has been a process of choice for making most electronic interconnections almost from the beginnings of the industry. Today it is deemed by many as an indispensable assembly process for electronic interconnections, yet many electronic interconnections from both the past and still today are without the use of solder. Following is a brief discussion of some still-viable solderless interconnection methods.

**Twisted wire connections:** The twisted wire interconnection is arguably the oldest form of electrical interconnection. It has been a method of first choice for years because no other process is required. That said, in many electrical systems the interconnection is augmented by a mechanical device such as a wire nut to assure long-term reliability.

**Wire wrap connections:** Wire wrap interconnections have been used by hobbyists for decades to make prototype electronic assemblies and as well by some OEMs for certain products. A special tool is used to wrap bare wire around a rectangular post, making a reliable, gas-tight connection in point-to-point fashion.

**Adhesive interconnections:** Many different types of adhesives have been used over the years to make electronic interconnections. Most often the adhesive is a mixture of metal particles (normally silver) and some sort of epoxy, and the connection can be isotropic or anisotropic. Even non-conductive adhesives have been used in some applications.

**Wire bonding:** Used for making interconnections on the vast majority of ICs to connect with lead frames, gold, aluminum and copper wires are all available, with aluminum wire bonding the most common.

**Resistance welding:** This is a process involving the use of momentary high current to weld copper ribbons to copper circuits. It has been frequently used for making repairs to traces on PCBs.
**Press fit connection:** Used for making interference connection between connector pins and plated through-hole backplanes as well as wire wrap boards.

![Press fit connection](image)

Figure 2.1: Examples of solderless interconnection methods used in electronics assembly.

![Conductive composites](image)

**Wire bond / Stitch wire**

Figure 2.2: Front and back side views of a wire wrap (no solder) interconnected board.
While there is modest but steady growth in interest and some movement in solder alloy-free assembly, based on disclosures such as that just described, incumbent technologies are very difficult to displace. This was noted by Dr. Mark Gostock, former technology transfer manager at University of Oxford’s ISIS Innovation in an interview where he observed that, “...there are going to be a lot of people, who make a whole lot of money from the way we do it now, who aren’t going to be happy when they hear what we have got.” It was a thought echoed and amplified by his colleague Chris Stevens, an academic and entrepreneur, who in the same story in *The Guardian*[^2-16] said, “The PCB industry in particular has already made a big investment in manufacturing infrastructure and they are not going to want to change.” Clearly these gentlemen understand the challenge of implementing change.

**WHY SOLDER IS USED AND WILL CONTINUE TO BE USED FOR ELECTRONIC ASSEMBLY**

Solder is a legacy technology with a substantial installed base and myriad suppliers of solutions. For this reason, solder is expected to see continued use into the future. Change happens slowly and it will take some time for the benefits of eliminating solder from the manufacturing process to sink in.

In the end, it will likely be the financial benefits of eliminating solder that will be the key driver of the change and not its myriad other technical benefits. Hopefully this book will help product designers with more entrepreneurial bents make that shift in thinking first for themselves as individuals with an appetite for change, and then for their companies.

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[^2-16]: Figure 2.3: Two other prospective approaches to manufacturing electronic assemblies without solder are shown.
CHAPTER 3
Benefits Analysis of SAFE Technology

It makes little sense to promote change if there is no benefit to come from it. As stated already, change is inevitable, but like evolution, if the changes made or sought do not provide benefit and improve chances for survival, the change could well cut off the branch.

Before discussing benefits, it is deemed worthwhile for the reader to get a basic idea of the process steps. Figure 3.1 is offered for that purpose. It is, however, only one of a number of different possibilities which might be considered but it provides a basic appreciation of the prospective simplicity.

Figure 3.1: The number of steps required for manufacturing SAFE assemblies are relatively small compared to traditional manufacturing.

1. Significant Economic Benefits of SAFE Technology
   One of the primary materials of interest discussed in this book is aluminum. It can make possible many of the benefits that follow. It is not insignificant that aluminum is the 3rd most abundant material on our planet (oxygen and silicon are 1st and 2nd, respectively). It comprises 8.3% of the earth’s crust. Because of its commodity status, aluminum is sold by weight regardless of thickness and it is less expensive per unit volume than composite materials with the price at roughly $1.65 per kg ($0.75 per pound in November 2016). Though aluminum is admittedly
somewhat denser than FR-4 laminate (2.8 g/cm³ aluminum versus 1.8 g/cm³ for FR-4), the amount of aluminum required can be very cost-competitive in the long run. In contrast, the price of polymers varies due to the volatility of the price of oil; there are advantages to being able to use a material such as aluminum, the price of which is reasonably predictable because of its global abundance.

Next, as will be made clear, the number of manufacturing steps is reduced, significantly reducing manufacturing cost. What should be highly evident is that the entire soldering process with its many steps and requirements is omitted. No stenciling of solder, no paste inspection, no reflow, no post-assembly cleaning, etc. Depending on the complexity of the design, as it has been estimated independently by a number of manufacturing experts, the final cost of such assemblies could be 25-35% lower than traditional methods (exclusive of the component cost). See Figure 3.3.
Figure 3.3: The simple cost comparison model above was prepared by Richard Otte, president of Promex Industries, in 2009.

The prices of equipment may have changed, but in general the assumptions in approach remain valid as SMT manufacturing technology has changed little over time. One can argue over certain costs but it remains that there are significant overall cost advantages possible with SAFE.

2. Reliability Improvement with SAFE Technology

Product reliability is a key factor in a company’s reputation. Unfortunately, it is not easy to assure with the complexities of the current manufacturing paradigm using solder. Reliability is the product of the many decisions made relative to all the important processing factors and functional elements of an electronic assembly. With solder being a primary source of failure, its elimination, including the numerous process steps associated with its execution, simplifies the processing. Simpler processes can be better controlled, improving both yield and reliability. Considerations which must be taken up and acted on include the electrical, environmental, thermal and mechanical performance requirements placed on the final product in its application.
3. Environmental Benefits of SAFE Technology
During the last few decades, concern over the environment has moved steadily into the consciousness of government officials, business leaders and the consuming public around the world. The term social responsibility is also often used to describe the concern; however, the fact that the industry makes products that impact the environment at the lowest possible level has become increasingly important. With that in mind, consider an electronic structure constructed principally of a material which is desirably and easily recycled, such as aluminum. Moreover, consider as well an assembly which requires significantly fewer process steps, less energy in production and fewer overall materials and one is on the road to making products that are more sustainable as well.

4. Reduced Legislative/Administrative Burden with SAFE Technology
Regulatory compliance has become crucially important to the manufacture of electronics. The European Union’s RoHS legislative mandate to eliminate lead from electronics solder has proven very costly, with billions of dollars needlessly wasted to solve a problem that could be much more easily managed by incentivizing proper electronic waste management. While there has been belated realization of that important idea, if one eliminates solder completely, this legislation and the need to chase manufacturers around to prove compliance with solder-related regulations is automatically made moot. Why? It is because the finished electronic structures that will be described in detail are all nearly all-copper interconnection systems. On the finished product, only the surface sites required for making electrical connection to the other system elements, such as switches, connectors and the like, need to have a contact finish.

5. Design Security Improvement with SAFE Technology
The electronics industry is highly competitive and the desire to keep designs secret for as long as possible is a highly prized goal for many manufacturers. However, for some of the market leaders, their products are torn down and exposed to the world almost immediately by enterprising entities that seek to profit by writing reports on the inner workings of the product, including component identification and their numbers. Such secrecy is also sought by makers of other products, especially military, automotive and aerospace applications. The manufacturing processes
used in SAFE constructions are made intrinsically more secure, placing the components on the inside of the assembly, hidden from view. This is not to say that a highly motivated and well-funded team of engineers could not divine eventually what is in the product, but it would take more time.

6. Improved Product Performance with SAFE Technology
Product performance is predicated on many factors, beginning with the chip. The on-chip performance is deemed to be as good as it gets and everything after the signal leaves the chip simply degrades it. One of the chief culprits is signal loss over distances—even very small distances as feature sizes on chips continue to drop. When solder is eliminated from the manufacturing process, so also are solder pads which can have parasitic effects. Moreover, components can be placed much closer together because there is less concern about interference during placement and cleaning under devices after solder assembly. There is also the prospective benefit of being able to provide better electrical isolation between components, especially when components are placed in cavities on a metal sheet such as aluminum (see Figure 3.1).

7. Assembly and Product Size Reduction
The size of an electronic assembly is a key factor, not only in delivering improved performance as mentioned previously, but it is also a highly desirable feature from a marketing and user perspective. Products built without solder can be substantially smaller than traditional products using solder for assembly. This benefit has both economic and environmental spillover benefits as well. Smaller products use less material and less energy in manufacture, which helps meet with sustainability objectives as previously mentioned. The lesser amounts of material used translates to less added cost to the assembly. The smaller, lighter products are cheaper to package and ship. In short, size reduction to the lowest practical level is a significant benefit, especially as the industry continues to increase focus on wearable electronic products. SAFE assemblies are ideally suited to meeting these objectives.

8. Amenable to Design Using a Fundamental Grid Pitch
When properly planned and executed, SAFE assembly designs can have
substantially fewer layers than circuits built using solder technology by using only components with a common grid pitch. To be fair, however, it is worth noting that some of the same benefits can be had using solder technology if attention is given to a few key details. The key is to select, to the extent possible, only components with terminations which fit a common grid. The concept can perhaps be most quickly grasped by viewing Figure 3.4. It is of a LEGO base with bricks of different sizes made to appear like an electronic module. It was assembled and photographed in approximately 1995 while the author was employed at the CSP pioneering company Tessera.

![Figure 3.4: A LEGO-inspired electronic module from ~1995. LEGOs can accommodate any component which has capture holes (lands) on the same basic grid and the proper diameter relative to the posts.](image)

Even then, the basic concept is not all that new. The electronics industry used this approach for many designs from the 1960s to the 1980s during the peak use of through-hole component technology. Breadboards for
hobbyists are still based on 100 mil grid. However, with the advent of surface mount technology, there were introduced a range of new families of peripherally leaded components which caused a sea change in planning for the future. The new components allowed for easier shrinking of their size. For planning purposes, a roadmapping concept called the “80% Rule” was adopted. According to the concept, each future lead pitch would be 80% of the previous pitch. The objective was to provide a roadmap for planning future electronic packages and supporting hardware and software for design and test. It arguably worked well for peripherally leaded components but when adapted for area array components it was a lost opportunity to recapture the benefits of earlier days (see Figure 3.5).

First, when all of the component leads have a common grid pitch and are laid out on such common grid, circuit routing is much simpler, more predictable and can generally be accomplished in fewer layers. In addition, electrical performance characterization is easier. Using the basic grid pitch, one can employ unique routing concepts such as one

![Image of Standard Practice and Improved Practice](image-url)
developed by Prof. Len Schaper and his colleagues at the University of Arkansas, specifically IMPS (integrated mesh power system). This allows meshing of power and ground with circuits and the astute designer can potentially reduce layer counts of 4, 6, and 8 layers for traditional approaches with no attention given to the grid concept down to as few as 2 metal layers in certain cases.

Figure 3.6 The IMPS concept for multichip module construction interweaves power, ground and signals in just two metal layers.

Figure 3.7: Multiple lead pitches and land sizes create a challenge for routing as illustrated in the graphic on the left.
9. Improved Circuit Routing
An artifact of the use of common grid in concert with the elimination of solder, there is possible a significant improvement in circuit routing. This also helps to greatly reduce layer counts if certain protocols are followed, as was just mentioned. The potential is illustrated in Figure 3.8.

![Figure 3.8: Microvias perform a vital role in high-density interconnection, allowing the designer to interconnect to terminations several rows deep on area array package devices as illustrated on the left.](image)

However, if the designer chooses to use solderless assembly, it is possible to reduce layer count by building up circuits on components using high-density interconnection technologies rather than attaching components to circuit boards. Note also that in area array packages, the solder ball can account for half of the mounted height of a component as illustrated in Figure 3.8 above.

10. No Solderable Finish Required on Components/No Solderability Testing Required
Maintenance of a solderable finish on both components and the circuit board is key to assuring a good solder joint. A great deal of care and testing is typically exercised to make this happen. When solder is removed from the manufacturing equation, the need for solderability testing disappears. As will be discussed later, under ideal circumstances
components will be provided with a copper finish allowing for a copper-to-copper interconnection between component and circuitry in the same manner as is used for making microvia interconnections on a circuit board. This is illustrated in the image on the right side of Figure 3.8.

11. Mechanical Performance Improvement
Mechanical considerations are a key part of the process of qualification for IC packages and electronic assemblies. By eliminating solder, the most common cause and site of failure in an electronic product—the solder joint—is also eliminated. When the components are encapsulated and held subsurface, the only thing that is required is that the plated vias and circuits are made to specifications. Shock and vibration failure, while still possible, are much better managed.

There is another matter which warrants discussion on the subject of improved mechanical performance, and that is the need to, to the extent possible, manage the issue of CTE (coefficient of thermal expansion) mismatch. In the world of electronics, a number of different elements found on the periodic table of elements are pressed into service. The two most important elements are silicon for ICs and copper for circuitry. These two fundamental materials have significantly different CTEs. Silicon’s CTE is approximately 3 ppm/°C and copper’s CTE is closer to 18 ppm/°C. Given the range of temperatures an electronic assembly sees during fabrication, the mismatch in expansion can be significant, and warping of the assembly is often manifested.

Bimetal Strip Model

Figure 3.9: The effect of CTE mismatch between Cu and Al shown highly exaggerated for clarity. (Note: Bimetallic strips are used in various types of thermostats to turn on and off heating and/or cooling systems.)
The use of engineered materials to manage the difference in expansion is very important. Eliminating solder and the solder process from the equation helps to ameliorate the problem to a significant degree. That said, by judicious use of materials such as aluminum to support components, the mismatch can be much improved (CTE of Al is 22 ppm/°C which is reasonably close to copper). Even so, there is still a mismatch which can create a bimetallic strip effect (e.g., warping of the assembly). Figure 3.9 illustrates the effect of mismatch in a highly magnified and exaggerated way. Moreover, as will be taken up next, aluminum is a very good thermal spreading material which helps to manage the heat when it is present.

Figure 3.10: Properly formed solder joint (left) next to a cold solder joint (right) where insufficient heat was applied, possibly due to a higher thermal demand caused by the design’s construction.

12. Improved ESD and EMI management
Electrostatic discharge (ESD) and electromagnetic interference (EMI) matters are increasingly important as the electronic products with ever smaller features have a higher risk of damage and are increasingly interconnected and operated without wires. One of the inherent benefits of total encapsulation of electronic components and their interconnecting circuitry is that the assemblies can be over-plated with a metal jacket. Within the assembly, wherein components are placed on a metal base
with cavities, the components can be mutually shielded from one another by metal walls or metal plated insulating walls between components. See again Figure 3.1 as well as Figure 3.11.

13. Embedded Battery Potential
Batteries are customarily not added to an electronic assembly until after soldering, because batteries cannot withstand solder temperatures. There are, in fact, specific recommendations from manufacturers that batteries should not be exposed to high temperatures due to risk of explosion. Depending on the materials and processes used in manufacturing without solder, batteries may in some cases be embedded in the assembly (see Figure 3.12).

14. Reduction in Testing for Faults
Testing is deemed to be imperative in modern electronics manufacture but the industry arguably does much more testing than is necessary (especially for hi-rel hardware) and that testing can frequently degrade both long-term reliability and performance. That said, the reader is reminded that components themselves should be of known good quality and burning in and testing of components is considered very important. This is because rework and repair—which are considered to be essential capabilities of traditional manufacturing—are possible only with great difficulty. It is another case of the adage, “First do the right things and then do those things right.”

15. Reduction in Inspection for Defects
The quality guru Dr. W. Edwards Deming said that one should either inspect 100% or zero. Inspection does not add value; it simply screens
for failures of the manufacturing process. It is far better to focus on making the process robust than to find its weaknesses after the fact. With that in mind, it is important to look at and measure certain attributes to understand the process health using statistical process control techniques. However, when it comes to solder joints, inspection is a crutch that seems to be used to excess. In that regard, one of the types of inspection that is now frequently and increasingly performed on electronic assemblies is X-ray inspection. This should raise a red flag, as radiation has been shown to damage ICs, yet there are scores of assemblers around the globe making product who have little to no knowledge of that; they simply want to make good solder joints and interconnects. They have discovered X-ray inspection and are using it enthusiastically, even multiple times on the same part, when creating 3-D stacks and sticking that device onto a board—the long-term effects of which are yet to be understood and fully appreciated.

16. Elimination of All Solder Defect and Failure Modes
If one eliminates solder from the electronics manufacturing process, it follows that all failures related to solder could be eliminated. Given the fact that a substantial percentage of defects and failures in electronic systems are found in solder joints, elimination of solder represents not only an opportunity to make a more robust product but also one that is substantially less expensive over the long haul.

17. Stable Optoelectronic Interconnection Platform Possibilities
Optoelectronics are vitally important in long-range communications, but they continue to be of interest and investigated as an option for short distances as well. In recent years, a number of groups and companies have built demonstrations and reported on the use of photonics for intra-board interconnections via embedded wave guides. One challenge
to traditional PCB technology is dimensional stability as alignment of the wave guide to the devices is vital. The use of aluminum as a substrate is highly advantageous in this regard as the optical channels can be formed directly in the aluminum by any of a number of different methods, such as etching or embossing. The channels can also be formed in polymer above the components as optical ports are commonly found on the bottom of devices. See Figure 3.13.

Figure 3.13: Optoelectronic channels require high precision alignment. An aluminum base material used as a component carrier is significantly more dimensionally stable than traditional PCBs.

18. Amenable to Overlapping of Components in the Assembly

Stacking of chip packages was first explored using dual in-line packages in the 1970s and ‘80s. Advances in the technology have been ongoing since and stacking of packages is presently practiced broadly within the electronics industry. Current stacking is predicated on the development of IC packages with terminations on top and bottom sides. The bottom side of the package is attached to the printed circuit board using soldering

Figure 3.14: Stacking of common IC packages one above another is shown in speculative constructions. The sequential buildup of plated interconnections and insulation layers using the methods described elsewhere in this text completes the assembly.
and soldering is used as well to attach the top component or components to the lower package. This allows for significant increases in package density. Solderless assembly is also amenable to using such packages, but it has the added vantage of being able to directly interconnect packages and discrete devices which are not electrically interconnected beforehand. Speculative examples of possibilities having two or more layers of interconnection are shown in Figure 3.14.

19. Greater Amenability to Unbalanced Constructions
Circuit designers are routinely admonished to make their PCB designs balanced from side to side to minimize the potential for warpage during soldering processes. The elimination of solder obviates much of that concern.

20. Sustainable Manufacturing Technology
Sustainability of manufacturing and delivery of product to an ever-increasing global population is of increasing concern to many in the global manufacturing community. However, there is no generally agreed upon definition of what sustainability really means. There are, however, think tanks staffed with researchers who are grappling with the definition. One such think tank is the Lowell Center for Sustainable Production. They have created a reasonably comprehensive guideline titled *A New Way of Thinking: The Lowell Center Framework for Sustainable Products*. Those seeking to make an effort to create products and processes which are sustainable can access the link above online at sustainableproduction.org.

Summary of Benefits
The present approach to manufacturing electronic assemblies has many limitations that can be circumvented by simple elimination of the soldering process. It is arguable that, in many situations, the capture of even one of the benefits just enumerated and discussed would be cause for making changes to the design and manufacturing process.

In summary, the reader is asked to consider carefully these benefits and their attendant risks. For those whose livelihoods presently depend on solder technology, it is suggested that they be even more critical and honest in their argument and analysis because it is believed that they will see the importance of accommodation and adaptation if they do.
CHAPTER 4

“First do the right things, then do things right”
Author unknown
SAFE/Occam Process Overview

To more fully appreciate the benefits of solderless assembly for electronics, it is important to understand the significant differences between traditional manufacturing and the methods being proposed. To help in that effort the reader is provided with a few charts and graphs designed to highlight the significant differences. See Figure 4.1.

**Simplified Solderless Assembly**

Figure 4.1: Conventional approach to electronic assembly is considerably more complex than a process where solder is not used (graphic courtesy of Tom Clifford).

**Process Options**

There are a number of different approaches to making electronic assemblies without solder. The most basic is perhaps wire wrap technology (refer back to Figure 2.1). It is also the most labor-intensive and limited largely to packages having through-hole leads. It is a method long used by hobbyists because it allows them to easily rewire electronic
assemblies and the process is performed at room temperature. Earlier in Figure 2.2 was shown an example of a wire wrap board with top and bottom views.

While a number of different types of constructions are possible under the umbrella of the SAFE concept, there but a few basic steps and common steps required to manufacture a SAFE technology product.

1. First (and most preferably), use only components which are packaged and are of known good quality and for ICs, burned in. It is also preferable that these components share a common lead pitch for their terminations, as discussed earlier.
2. Accurately place the components either face up or face down (depending on process approach followed) onto a carrier which may be either permanent or separable.
3. Encapsulate the components using an approach compatible method and material (there are numerous prospective options). This holds the components in place for subsequent processing.
4. Depending on method, either clean the contacts or cover them with a polymer.
5. Access terminations by method-suitable technique (e.g., laser drilling or photo defining using photo polymer or other technique).
6. Create circuit layers simultaneously, making interconnections to component terminations. This can be done either by direct printing of conductors or by image and etch processing.
7. Coat assembly with additional insulation and conductive layers to meet design requirements.

It is a short list and significantly shorter than traditional methods. To better appreciate the potential process savings compared to more traditional manufacturing, the following two charts are offered in Figure 4.2.

In full disclosure, many critics of the concept have stated that having wet processing equipment proximate to expensive SMT equipment is a “non-starter.” However, in the manufacture of PCBs, expensive equipment is also used and it is separated environmentally by walls and doors. Processing need not all be performed in the same room. That said, there is the possibility of having all the necessary processes and equipment in one room when insulation and circuits are sequentially printed using conductive and insulating inks. Consider for example the concept in Figure 4.3.
Figure 4.2: A comparison of process flow between traditional and solder alloy-free processing showing the difference in process flow and reduction in number of process steps required.
Solderless Assembly for Electronics: The SAFE Approach

Interconnection Structure Overview
The range, in terms of shape and size of electronic interconnection structure, includes all of the more familiar, traditionally built electronic assemblies, but it is much broader in scope as will be shown. There is much more latitude in terms of materials and processes which can be used in the manufacture of solderless assemblies. It is not the intent within this section to describe all of the possibilities because variations on the general theme are arguably limitless or at least bound only by the imagination of the designer.

Exemplary Assembly Structures
There are several possible methods of fabricating rigid electronic assemblies. The structures are similar in that they are designed to have all interconnections made without the use of solder. However, they are unalike in terms of the manufacturing processes that are used to achieve them. Following are descriptions of some of the basic types.

Encapsulated Component Assembly
Encapsulated component assembly is arguably the simplest type of interconnection structure. It is also the method first used to demonstrate the efficacy of the process. The process steps are relatively simple, yet there are many possible variations within that simplicity.

The first step is to accurately place the components onto a tacky surface using pick-and-place machines. The components are then encapsulated in situ, using an epoxy encapsulant, for example. A vacuum may be required to remove any bubbles and assure complete encapsulation of the components and all their surfaces. When the encapsulant cures, the component-embedded encapsulated assembly is removed and layers of circuits and insulation are built up as required to make all
interconnections between the components. An injection molding step using a thermoplastic material may be substituted for the epoxy encapsulation. There are reportedly some advanced injection-moldable materials with high flow capability which could be useful in numerous applications. One word of warning about encapsulants is that they can be expensive, and thus may be best suited to prototyping rather than production. Thermoplastics, on the other hand, may prove a viable alternative. To help visualize this process, see Figure 4.4.

Figure 4.4: A conceptual drawing showing an integrated piece of equipment capable of all process steps for the manufacture of an encapsulated SAFE assembly.

Cavity Structures for Component Capture
As an alternative to encapsulating components in situ, it is possible to create structures which capture and hold the components in their desired locations. The manufacturers of printed circuits have used similar methods to embed discrete devices in the circuits before the lamination process. In such cases the pre-preg or B-staged epoxy glass material used to bond the layers is often pre-punched to create a pocket into which the components can be placed before lamination. Following are descriptions of alternative methods which are better suited to the creation of solderless electronic interconnection assemblies.
Figure 4.5: An example of a molded or machined carrier base, both before and after the components are placed into cavities.

Punched or Routed Base Material Stack
As an alternative to molding, it is possible to use CAD data to create tools for punching or routing thin layers of a chosen material (e.g., aluminum) that can be stacked and subsequently bonded to a stable base before component placement into the resulting cavities. To account for differences in component height the layers may have areas that are not routed or punched as illustrated in Figure 4.6.

Figure 4.6: An example of a punched or routed cavity structure designed to accommodate components of different heights. An alternative approach is to insert shims into cavities where required, but simpler engineered solutions should be employed when possible.
Flex and Rigid-Flex Assemblies

Flex and rigid-flex circuit technologies are highly prized by many circuit designers for their ability to free the designer from the normal constraints of rigid printed circuit boards and it is possible to manufacture these types of circuits without the use of solder. What will be illustrated and discussed in this section is limited for the same basic reason that it is necessarily limited in the discussion of standard flex and rigid-flex circuits, and the reason is that the limitations are typically defined by the imagination rather than processing capability.

![Diagram of flex circuit assembly](image)

Figure 4.7: An illustration of one approach, out of many possible, for manufacture of a simple flex circuit assembly created without the use of solder.

Rigid-flex circuits are arguably even more versatile than simple one- and two-metal-layer flex circuits. It is possible to make such assemblies without solder. Again, a visual description of the process is perhaps easiest to grasp and is offered in Figure 4.8.
Yet another potentially viable approach to making rigid-flex without solder is one that employs aluminum in its construction as a base material. Following is a verbal description and a graphic (Figure 4.9) to help understand the processing steps.
First, a sheet of aluminum (other metals are also possible if desired) is prepared with cavities that can be either machined (chemically, mechanically or laser), embossed into the metal sheet using punch tooling, or cast. One or both sides of the metal can be provided with components. As mentioned in earlier descriptions, the cavities that are to receive the components are ideally formed such that the depths will match the components’ height, so that when components are placed into their assigned cavities with leads facing up, the lead terminations will be flush with the surface. While the use of bare die is possible, the IC components to be used are ideally packaged (CSPs are very well suited).

While untreated aluminum can be used effectively for many applications, there are some advantages in other applications to either treating or coating the surfaces. Anodizing of aluminum is a very common industrial process which results in the surface of the aluminum being converted to alumina (Al₂O₃), an insulator. Another alternative is to coat the aluminum with an organic coating such as an epoxy, which can be done by powder coating or painting by electrophoretic or electrostatic methods, resulting in a very uniform coating over the entire substrate.

After the components are placed and affixed permanently on one or both sides, layers of flexible insulation are applied to one or both surfaces of the metal sheet covering the components. A flexible clad laminate may also be used if desired. At this point, the assembly can be processed almost as if it were a standard rigid printed circuit with high density build-up layers on one or both sides, using lasers to drill holes down to access component terminations and commonly practiced plating and imaging processes to create the circuits.

Once all of the circuit layers are complete, a final flexible film (i.e., cover film or coverlayer on one or both sides) is applied, leaving open any features required for interconnection at the next level. The coverlayer and/or flexible base film will ultimately need to be absent from the areas that are going to require flexing, as well as those that will define the outline of the completed circuit. This can be accomplished by mechanical, chemical or laser methods, either alone or in combination with one another. Once the metal is exposed, it can be etched using a suitable chemistry either completely or to some predetermined depth if the designer desires to leave a conductive path between rigid component-bearing areas.
When all of the required interconnections and circuits are added, the assembly can be partially machined to thin the metal carrier enough to allow the residual metal to easily bend and, if the metal is thick enough, hold its shape after bending. For the subject aluminum rigid-flex constructions, alkaline chemistries such as solutions of sodium hydroxide and sodium gluconate are suitable for etching aluminum. However, other chemistries such as ferric chloride are also suitable. In fact, ferric chloride is nearly universal in terms of its range of applicability as a metal etchant.

The process steps just described are illustrated in Figure 4.9.

Figure 4.9: A novel approach to design and manufacture a rigid-flex circuit.

**Thermal Management Constructions**

When solder is eliminated from the manufacturing process it becomes possible, in the words of one prominent thermal management consulting
engineer, “to solve thermal problems on the front end rather than the back end of the design and manufacturing process.” Metal core structures, which have been described numerous times in this book, make that possible. It is even conceptually possible to place a heat pipe at the center of the electronics assembly either in the manufacturing process or by wrapping the ends of a rigid-flex circuit around the heat pipe and bonding it to its surfaces. This is illustrated in Figure 4.10.

Figure 4.10: Thermal management is increasingly important as device temperatures rise due to power required for higher operational frequencies. Solderless assembly technology offers unique potential for managing heat early in designs rather than as an afterthought.

**Metal Encapsulated Electronic Assemblies**

Another unique possibility that is an artifact of electronic assemblies wherein the components are fully encapsulated is the potential to plate the finished assembly with metal leaving open only those features which are required for interconnection at the next level (this was mentioned

Figure 4.11: When the components are fully encapsulated in insulating polymer, it is within the realm of possibility to overplate the entire assembly with metal. Such metal serves not only to provide electrical and electronic protection from the effects of EMI or ESD but also from the effects of moisture as the metal is impervious to moisture ingress.
earlier in the benefits chapter). This results in assemblies that are electrically sealed and shielded from EMI and ESD, but also assemblies that are close to being completely hermetic and thus immune to concerns related to moisture ingress into the assembly. Examples of what such assemblies might look like are illustrated in Figure 4.11.

**Stacking of SAFE Assemblies**

Another unusual possibility is the stacking of completed assemblies as illustrated in Figure 4.12 where assemblies are shown interconnected using mezzanine interconnection methods such as buckling beams or other vertical connections. The approach is somewhat analogous to designing a building with elevators in strategic locations to allow traffic to move efficiently from floor to floor and office to office. Moreover, as is shown, it is also possible to make optical interconnections because optical ports are normally on the bottom of components.

Figure 4.12: SAFE assemblies can be stacked using mezzanine connectors.
Preparation for Design
Typically, design drives advances in manufacturing technology. Designers lead the process flow of electronic manufacturing and are nearly constantly challenging producers to come up with ways to make their visions real. Unfortunately, manufacturing typically abhors change. Manufacturers are most comfortable producing the same type of products today and tomorrow as they did yesterday. But without challenge very little progress can be expected.

To take full advantage of SAFE concepts, the circuit designer must carefully consider every aspect of manufacturing. The elimination of solder opens the doors to many new opportunities but to achieve them there is need to think and choose carefully how the structure will be laid out and manufactured.

Component Selection
In keeping with the principles of Occam, it is hoped that the designer will see the possibly significant benefit of selecting and using components which are best suited to the process. As described elsewhere, the components best suited to the task are those which have terminations on a common grid pitch. Recall the image of the LEGO module shown earlier and the discussion of its benefits.

It is hoped that this technique will allow the designer to design his electronic product with the least number of transistors possible.

Preferred Component Finish
Presently nearly all electronic components are provided with a solderable finish. These finishes include lead-free solders, silver, and nickel-gold among others. When solder is not required neither is a solderable finish. The preferred finish is in fact bare copper. Unfortunately, only a few suppliers of electronic components presently supply components with a copper finish. Most of these are presently discrete components (see Figure 4.13). There are benefits to eliminating a solderable finish, one of which is that, when component terminations are of solder, it eliminates concern about buildup solder on contactors used for testing and/or burn in of the electronic components.
Preferred Component Types
As stated previously on more than one occasion, the preferred component types for solderless assembly layout are of two primary configurations: land grid arrays (LGA) and quad flat no-lead components (QFN). Under ideal conditions all components desirably have a common thickness. This is not an impossible goal but it requires vendors of components to be a bit more thoughtful and proactive in considering their construction options.

Component Placement and Capture
Standard SMT equipment can be used for picking and placing the components either on a tacky surface as described above or into cavities as described earlier. One important difference is that when components are placed in cavities they must necessarily be placed upside down. That said, it is also possible with cavities to place the component terminations down and provide a small amount of adhesive at the bottom of the cavities within the body of the component carrier. The adhesive can serve two purposes: first, it serves to capture and hold the component in position and second, it serves to level components making sure terminations are all coplanar. The coplanarity
of component terminations can be very important depending on the tools and technologies which are employed when building up layers of circuits.

**Package Under Package (PuP) Constructions**

Package on package (PoP) interconnection solutions have been available to designers for at least three decades. One of the first uses was in the stacking of dual in-line packages to increase memory in early memory modules. However, with the recognition that there will be a sunset in Moore’s law relative to on-chip integration, there has been a surge of interest in packaging stacking solutions both homogeneous and heterogeneous. With SAFE/Occam approaches to manufacturing, another option is available: package under package. Figures 4.14 and 4.15 convey the nature of the PuP interconnection potential. It is possible that the technique could be applied to components that are to be soldered to the surface, but it is uncertain what the quality and yield might be.

While Figure 4.15 shows a component under a component, Figure 4.16 shows discrete devices such as chip capacitors and chip resistors bonded to the surface of the component, providing additional performance and space-saving benefits.

Figure 4.15: A 44-lead QFN fits comfortably in the cavity formed by the leads of 44 I/O J-leaded component. The mated pair of devices could possibly be placed and soldered as a unit if desired.

Figure 4.16. Package under package (PuP) assembly is possible and offers unique potential to build unusual interconnection substrates. Moreover, the use of a low-cost and highly thermally conductive aluminum as a base is possible when solder is not employed to make package and device interconnections.
Note that while only a single-sided assembly is illustrated, two-sided assemblies are possible and it is also possible to stack the completed assemblies to create even higher-density structures, with the aluminum bases potentially serving as ground and/or power layers.

**Printing Circuits Using Conductive Inks**

The conductivity of printed inks is not yet as good as copper metal but it is getting better all the time as improvements in materials and processes come on line in the service of the printed electronics branch of the industry. Suitable methods for printing conductive inks include screen printing, stencil printing, and inkjet printing.

**Copper Plated Circuits**

The printed circuit industry has been using copper plating to make circuits on PCBs for many decades. Copper foil-clad laminates have been a mainstay for subtractive processing for more than half a century. However, with the advent of HDI technology, additive and semi-additive technologies have evolved and are increasingly a mainstay method for today's higher density electronic assemblies. To make a SAFE circuit, the component board is coated with copper and the circuit layers built up sequentially in a manner virtually identical to the methods used for today's increasingly common HDI boards. The difference is that solder lands are not required, making it possible to complete the circuit with fewer layers.

**Hybrid Processing of Circuits**

Advances in circuit fabrication technology are making possible new techniques which are hybrids of printing and plating. One example is a process introduced by eSurface[^49] in Carlsbad, California.

The technology is executed by coating the laminate in a proprietary solution and then exposing it to UV to catalyze the circuit pattern and developing the pattern in water. The circuits can then be plated with copper. The process is very attractive in that the number of processing steps is less than traditional processing, and in a manner consistent with the objectives of Occam/SAFE assembly; it reduces the complexity of manufacturing thus anticipating good control of the process and hence higher yields.
Another promising solution has recently come to my attention for producing circuits on the surface of solderless assembly component board structures. This one is from Averatek Corp, in Silicon Valley. The technology is additive and is advertised as being capable of forming very fine yet highly conductive circuits onto the surface of substrates. A more complete description of the technology can be found on their website.

**Resistor-in-Via**

When high-temperature soldering is not required, alternative processing methods become possible. One example is the formation of resistors within the vias of a circuit. The concept seems best suited to termination resistors. It is a relatively simple process because the holes are of chosen diameter and the insulation material of known depth. All that is required is to choose a resistive ink of appropriate value to create a resistor of predictable and repeatable value with reasonable tolerance. The process is illustrated in Figure 4.17.

**Integrated Resistor-in-Via Processing**

![Image of resistor-in-via process](image)

**Figure 4.17:** Resistors can be created directly at the point of need in Occam processing.

Note also that component leads do not require a solderable finish. In addition, nonfunctional lands on the package do not require processing, thus opening up real estate for circuit routing.
Discussion and Practical Demonstration
With all of the foregoing discussion for background, it is now possible to recap and provide some summary discussion for review. Figure 4.18 shows a practical example/demonstration of what can be achieved when solder is not required. All of the pieces of the puzzle come together in a redesign of a circuit assembly.

Figure 4.18: Shown to relative scale is a comparison of an original circuit design using traditional manufacturing methods and a redesign of the same product board using Occam design principles, including selection of components having only terminations on a common grid pitch of 0.5mm. Design rules for features are identical for both designs.

One reason components are normally placed further apart than needed in a design is because room must be left to facilitate flux removal and cleaning beneath the components after soldering. In addition, there is need to provide space for the removal and replacement and/or rework of the components when problems related to the soldering process inevitably arise. This is largely made moot with a properly designed SAFE assembly. In contrast, any attempt at using normal lead-free solders with an aluminum circuit board would likely end up poorly with many cold joints and/or thermally damaged components.
To amplify and better appreciate the comparison in Figure 4.18, the following results are offered:

1. The new design is ~70% smaller in terms of total area.
2. The new design folds into an assembly with a footprint roughly 15% of that of the original design with minimal increase in height.
3. Though the density of aluminum is greater than FR-4, (FR-4=1.8 gr/cm3, Al=2.7gr/cm) the total weight of the assembly is projected to be ~55-65% less than the original.
4. The rigid-flex structure chosen is amenable to the separation of digital and analog circuitry and thus the potential for better control of the energy created by analog devices and power supplies exists.

In summary, the design of an electronic assembly using Occam principles and the SAFE manufacturing approach can provide powerful advantages when the desire is to reduce the size of the electronic assembly—create a more reliable assembly—one which can provide many additional benefits. It has been shown that there are clear benefits from solderless assembly in terms of making designs smaller. Such designs, it is also believed, will prove much more reliable than current approaches using solder for assembly.
ANNEX
Supporting and Resource Materials

There are numerous technological solutions that are in development and ready for deployment which appear to have parallel/synergistic potential relative to SAFE/Occam. Provided here are a few examples for the reader's consideration.

**Green Arrays Multicore Technology**
Green Arrays was founded by Chuck Moore, the inventor of Fourth Programming language. His multicore processor invention was developed in support of it to make one of the more efficient solutions available. One small example is the GA144 multi-computer chip. It is designed to give the designer options that have never before existed and to place them under the product designers’ control by writing software. (greenarraychips.com)

**Terecircuits**
Terecircuits has developed a unique technology capable of placing extremely small devices (down to 100 micrometer square and 25 micrometer thick) accurately and at high rates by using a special light-sensitive adhesive to bond and release the chip devices where required. (terecircuits.com)

**Promex Industries**
Promex was an early investigator into the Occam concept. Visit their site for a technical paper with process description and analysis. (promex-ind.com)
Printed Conductor Research

A great deal of research is ongoing around the globe in the area of printed conductors for electronics and there are many sources for gathering information about current research. The following paper titles and abstracts can be found on the Royal Society of Chemistry website in the Journal of Materials Chemistry C.

Low-Temperature Sintering Highly Conductive Silver Ink for Flexible Electronics
Bhat, K, et al

Abstract
A synthesis procedure for development of a durable, particle-free and low-temperature sintering silver organic precursor (SOP) ink by using low boiling-point mild organic complexing ligands is described.

Solution-Based β-diketonate Silver Ink for Direct Printing of Highly Conductive Features on a Flexible Substrate
Chen, C, et al

Abstract
Conductive silver lines were fabricated by inkjet printing on the flexible polyimide substrate using a silver precursor as the ink.

A Novel, Facile, Layer-By-Layer Substrate Surface Modification for the Fabrication of All-Inkjet-Printed Flexible Electronic Devices on Kapton
Fang, Y., et al

Abstract
Kapton HN films were surface modified, for the first time, by taking advantage of their additive and using only weak polyelectrolytes, for all-inkjet-printed flexible electronic devices.

Development Of Coated-Wire Silver Ion Selective Electrodes on Paper Using Conductive Films of Silver Nanoparticles
Janrungroatsakul, W., et al

Abstract
Films of silver nanoparticles are used for the first time as electrical conductor and ion-to-electron transducer to fabricate coated-wire ion selective electrodes on paper.

Conductive Silver Inks and Their Applications In Printed And Flexible Electronics
Venkata R., et al

Abstract
Conductive inks have been widely investigated in recent years due to their popularity in printed electronics (PE) and flexible electronics (FE). This paper looks at silver base conductive inks and some of the applications.
Assisted Sintering of Silver Nanoparticle Inkjet Ink on Paper with Active Coatings
Öhlund, T., et al

Abstract
Coated paper substrates were custom-designed and shown to assist low-temperature sintering of inkjet-printed silver films. A built-in active sintering agent induced room-temperature sintering.

References


[3-32] “A New Way of Thinking: The Lowell Center Framework for Sustainable Products.” PDF, Nov. 9, 2009; sustainableproduction.org

About this Book

Solder has been used to make electronic interconnections since the earliest days of the electronics industry. It has been a useful method and will likely see continued use well into the future but is it imperative that solder be used to make all electronic interconnections?

This short book was created to open the eyes of the reader to a new world of possibilities where the soldering process and all of its limitations and problems are avoided. It was designed to challenge the widely held belief that solder is a requirement. The book enumerates the numerous potential advantages of eliminating solder including economic, environmental, reliability, design efficacy and security. In addition, this book provides numerous examples of prospective structures that might be built simply by reversing the manufacturing process—that is, rather than building a printed circuit board and soldering components to it, build a “component board” and then build up circuits on its surface.

About the Author

Joseph Fjelstad is a 45-year veteran of the electronic interconnection industry and serial entrepreneur. He is also founder and president of Verdant Electronics, Inc. The company focused on the development of lower cost, more environmentally friendly and more reliable electronic products to meet the needs of both the most advanced products, as well as products for the world's most disadvantaged peoples.

Joseph is a globally recognized author or co-author of several books on electronic interconnection technologies, including Flexible Circuit Technology, 4th Edition; Chip Scale Packaging for Modern Electronics; and An Engineer's Guide to Flexible Circuits. He is also a magazine columnist and commentator, educator and innovator in the field of electronic interconnection and packaging technologies.

A frequent keynote speaker at conferences around the world, Mr. Fjelstad has been the recipient of a number of industry and corporate awards over his career. As an innovator, he holds more than 180 issued U.S. patents and numerous international patents issued or pending.