Spring Contact Probe Technology in Product Connector Applications

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Preface

This book can profoundly change the performance and marketability of the products the reader designs. It is intended to introduce design engineers to the concept of using spring contact probes as electromechanical interconnects.

Spring contact probes can make a product more reliable, more rugged, easier to assemble, and cheaper to produce. Hundreds of companies in a wide range of industries are already incorporating spring contact probes as connectors in their products. This book is intended to help other companies to catch up; if the readers’ company has already begun using spring contact probes, this book will help the reader to expand and refine the employment of this technology.

*Spring Contact Probe Technology in Product Connector Applications* is in one part a detailed study of spring contact probes as a connector technology. An engineer who has read this book will understand spring probes much more thoroughly than those who have not, even more so than those engineers who have been employing spring probes in their designs for a number of years.

An engineer who has read this book will be better equipped to choose between available connector technologies, and to justify that choice. The book also helps its readers understand spring contact probes in the context of other available connector technologies. All connector types which might normally be contrasted with spring contact probes are considered. Each is examined and its benefits and disadvantages are discussed, and then compared to the corresponding aspects of spring contact probes.

Often the best way to understand a technology is to see it in action. For that reason, the balance of this book illustrates and explains several existing applications of spring contact probes as connectors. Each application demonstrates a way to take advantage of one or many of spring contact technology’s unique benefits. An understanding of these applications and the motives of the engineers who developed them will allow the reader to gain a clear view of the ways spring contact probe technology can improve their product.

This book was published by Synergetix, a manufacturer of spring contact probes and connectors which incorporate probes. Many of the technologies and techniques for spring contact probe design and manufacture are unique or proprietary to our company. While every attempt has been made to protect this book’s objectivity, the general nature of the information it contains and some of the concepts discussed in this book are only available from the manufacturers. Engineers who wish to learn more about spring contact probe technology or see physical samples of exemplary applications are advised to contact Synergetix directly.
Basic Spring Contact Probe Technology

Introduction

Growing daily in sophistication and utilization, spring contact probes are an exciting contact technology that is becoming a primary consideration in the connector world. Product engineers are incorporating probes in cellular phones, military electronics, aerospace electronics, medical devices, and the most cutting-edge portable devices. Designers select from probes that offer exceptional DC or RF performance, controlled impedance, very low profiles, semiconductor scale pitch, or million cycle reliability; however, probes offer design engineers an almost infinitely customizable interconnect, and the most sophisticated of those engineers who prefer spring contact probes are familiar enough with them to specify their design in close collaboration with probe vendors, combining the above features to form precisely the best probe for their particular application.

This chapter will assist the reader in gaining a deep and thorough understanding of spring contact probes. Through study of spring contact probes, product engineers can gain mastery of this crucial and emerging technology.
Fig. 2
Effect of Crimp Location on Overall Length

Fig. 1
Typical Probe
**Elementary Construction**

Spring contact probes are telescopic, electromechanical interconnects. They typically consist of one or more contact members [often referred to as the plunger(s)] and a helical coil spring, housed within a conductive tube (normally termed a barrel). Figure 1 shows a typical spring contact probe design.

The plunger is retained within the barrel by a crimp. This crimp stops the plunger from coming out of the barrel, and the location of this crimp determines the degree to which the plunger extends from the barrel in the probe’s normal condition. If the crimp is moved further down the barrel, the plunger will be stopped at a deeper position within the barrel, and the overall length of the probe in its open state will be shorter (see figure 2).

**Compression and Resulting Mechanical Forces**

The crimp is usually made such that the plunger compresses the spring to some degree in the open condition. The plunger, even when the probe is at rest, is in a state of spring tension. This initial tension is referred to as the “preload force” of the spring.

When the plunger is pushed down while the barrel is held motionless, force builds in a linear fashion as the helical coil spring is compressed. The plunger moves within the barrel, and its downward travel is limited by one of several design features of the probe. If the plunger is shorter in its extension from the barrel than the available amount of travel as determined by the other features of the probe, downward travel of the plunger will be limited by the disappearance of the plunger within the barrel (see figure 3a). If the plunger is longer than the available amount of travel as determined by the solid height of the spring (the overall length of the spring when each coil is compressed into contact with its neighbor), then the compression of the probe stops when the spring reaches its solid height (see figure
3b). Alternately, the probe designer can provide a feature either inside the probe (figure 3c) or on the exposed plunger surface (figure 3d) which arrests travel. When the probe reaches its fully compressed state, any further compression results in forces being exerted against the probe’s structure. As such, the force of compression ceases to be driven by the spring and becomes a function of the material strength as the limiting factor, and rises towards infinity. Since it is most useful to understand the compression force in relevance to that created by the spring itself, probe manufacturers typically pick a random point (2/3 of the available travel is a common value) at which to rate the probe’s compression force, rather than specifying the force at full compression.

The spring force is thus usually expressed in grams, ounces, or most precisely in Newtons at the “rated travel” of the probe. For example, a probe whose spring requires two ounces of force to compress to two thirds of its rated travel has a two ounce “rated force.”

**Estimation of Forces**

Since compression force is primarily determined by the force required to compress the helical coil spring,
force at any degree of compression may be predicted fairly accurately if the spring force at preload and at rated travel is known. A simple graph can be drawn. The example shown in figure 4 is for a probe with a 2 ounce preload, a rated travel of 2 mm, and a rated force of 4 ounces. In the example, the estimated force of the probe at half of its rated travel, or 1 mm, is 3 ounces.

**The Influence of Friction**

Friction is a contributing factor to compression forces that must be considered in addition to the very linear and predictable force imparted by the spring. Friction will vary with the degree to which the compression of the probe is non-linear (referred to as the side load). The surface finish, lubrication, and other mechanical characteristics of the plunger and barrel-bearing surfaces will influence friction. As such, the component of compression force contributed by friction is very difficult to predict. Allowance, in some cases considerable in nature, must be made for the forces created by friction. This should be carefully considered when specifying probes for applications where force is critical.

**Receptacles**

In some applications it is useful for probes to be easily replaceable. Probes might then be used together with an
additional housing tube (referred to as the receptacle or socket), which is permanently mounted in place and has an electrical connection established to it, often by means of a wire. Figure 5 shows a typical receptacle, and figure 6 shows that same receptacle mounted in a plate with the probe installed and a wire attached by means of a crimp termination.

The receptacle will typically have features to retain the spring contact probe. The most common of these are referred to as detents (figure 5), which are small dents in the side of the receptacle tube that intrude into the receptacle’s inside diameter. When the probe is inserted into the receptacle, these detents stretch slightly, allowing a force fit. The detents can be used for a limited number of cycles with little change in retention force. They provide a wiping electromechanical contact from the receptacle to the probe barrel, and form a gas-tight seal.

The receptacle normally narrows or is closed at the bottom, to stop the insertion of the probe at a specific point. Frequently, this will cause the top of the probe barrel to be flush with the top of the receptacle.
Alternately, the system may be designed to allow the probe barrel to protrude slightly, for easier removal of damaged probes.

The receptacle will almost always include some sort of feature, typically in the form of a tail, which allows for the termination of a wire to the receptacle. This might take the form of a square-post wire wrap tail, or a solder cup, or an open end to allow for the crimping of wire into the receptacle. It can even have a smaller built-in probe as its termination, allowing for wireless interconnection as described below. See figure 7 for an illustration of the various available terminations.

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Fig. 7
Receptacle Terminations
In some cases, it may be preferable to allow the probe to interpose between two electrical contact points, rather than having a wire carry the signal to another point. For example, either a probe, as described above, or its receptacle, might be soldered into a plated through-hole in a printed circuit board (see figure 8). The trace on the printed circuit board subsumes the role of the wire that might otherwise be attached to the receptacle. This is the most common interconnection methodology when probes are used in connector applications.

If a probe is designed to be directly soldered into a PCB, it will normally have a feature such as a flange added to its barrel to control the depth to which it passes through the printed circuit board (see figure 8). Alternately, the spring contact probe can be contained within a...
header to control height while at the same time simplifying handling (see figure 9).

The probe can also be built with a plunger in each end of the barrel (see figure 10a). The probe can then be held motionless in the middle, and a printed circuit board or other contact target can be compressed against each end (figure 10b). In a variation on this technique, the probe can be made in a single-ended fashion, and allowed to “float” within its housing (figure 11), thus permitting it to interpose between two printed circuit boards or other contact targets.

**Mechanical Design Limitations and Considerations**

Probes are typically designed within certain mechanical constraints. These constraints are determined by the intended application of the probe. Very often, a desirable mechanical characteristic in a probe is limited by an opposing characteristic that is also desirable. These relationships are examined in this section.

**Diameter: Robustness versus Pitch**

The dominant diameter of a spring contact probe is chiefly limited by the final mounting arrangement. When other probes are the most proximate entities, this constraint is generally spoken of as “mounting centers,” “center-to-center spacing,” or “pitch” (figure 12). This is the distance from the center axis of one probe to that of another. For example, if two probes are mounted to contact two points that are 2 mm apart, those probes may be no greater in
a desired probe diameter of no greater than 1.5 mm is required for this example. If a receptacle is to be employed, this diameter must be considered as well.

However, the limitation of probe diameter for pitch considerations must be balanced with the resulting ruggedness of the probe. If the probe is to be exposed to non-linear compression forces, it must be of sufficient diameter to ensure that those forces do not overcome the material strength of its components.

**Working Clearance: Accuracy versus Manufacturability**

The plunger and barrel of the spring contact probe assembly are typically manufactured using sophisticated precision techniques; nonetheless, the probe manufacturer must allot a tolerance range for the finished dimensions of the probe components. Probe manufacturers must ensure that, when the plunger is at its largest possible diameter (nominal + tolerance) and the inside barrel diameter is at its smallest, sufficient space still exists to allow the plunger to travel freely.
The nominal space between these two components is referred to as the probe’s “working clearance” (figure 13). Selection of materials and the precision with which the probe components are manufactured influences the maximum value for the working clearance, as do the relative sizes of the components. A probe which has a large working clearance is easier to manufacture using the most cost-effective techniques; a probe with a tight working clearance may be more expensive, but will have the nonaxial deflection of the plunger limited more precisely.

Nonaxial deflection can create excess friction, contributing to high or variable compression forces and excessive wear. Furthermore, a probe with a large working clearance requires a larger target to ensure it strikes its target accurately, and a large working clearance increases the chance of “centering” (page 27) resulting in poor electrical contact.

**Length: Bearing Surface versus Spring Capacity**

In many applications it is desirable that the probe be relatively compact. As will be discussed in detail, probes that carry signals of relatively high frequency tend to perform better if shorter in overall length. Also, connectors made from probes are limited in their height by the available space within the final application. As consumer electronics become increasingly miniaturized so in turn must the connectors inside of them. Thus, design engineers specifying or selecting spring contact probes for inclusion in their products often seek to have the lowest-profile contacts available.

However, reduction of overall length results in a reduction of the barrel’s internal cavity. Within the barrel, the available space must be divided between the retained length
of the plunger and the spring (figure 14). Plunger retained length, or that portion of the plunger which is inside of the barrel in the probe’s open state, influences the relative length of the bearing surfaces — which control the linearity of the plunger’s travel within the barrel. Given the same working clearance, available radial deflection of the plunger is increased when the bearing surface is shortened. Figure 15 shows a probe with a short bearing surface and its radial deflection versus one with a long bearing surface. Thus, probes with less retained plunger length will be less accurate and more prone to binding and wear from sideload.

However, if bearing surface is increased at the expense of spring cavity, the spring design might be compromised. This could affect force, deflection range, or probe life as detailed below.

**Springs: Force versus Stroke versus Mechanical Life**

When designing springs, it is typical that the spring capacity of the probe is predetermined by the overall length of the probe and the minimum bearing surface required. Within the available spring cavity, the probe designer must balance three elements: the compression force deliverable by the probe, the deflection range of the plunger, and the mechanical life of the spring. A properly balanced probe design, where overall length of the probe assembly is relatively unlimited, can easily realize a several-million-cycle fatigue life, while still delivering an adequate force to the target that ensures good contact resistance and at the same
time has a large range of compliance. If probe overall length is limited, then either the bearing surface of the plunger, the spring force, or the probe’s mechanical life must be compromised.

**Materials and Manufacturing Techniques**

As noted, spring contact probes are typically constructed from a barrel, a spring, and one or more plungers. Each of these elements can be manufactured from a wide array of materials using many different techniques. Some of these are discussed on the following page, but innovations in this aspect of spring contact probe design are continuous.

**Springs**

Springs are typically the lowest-cost component of a spring contact probe and are not usually difficult to deal
with in terms of production capacity. Their design considerations are often very challenging, but the art of spring winding is fairly well developed.

Springs may be made from a high carbon steel known as music wire. Music wire has very high tensile strength, and is used to get high forces with long mechanical life. Music wire is highly magnetic, is the easiest material to stress-relax through overheating (see chart below), and is subject to corrosion. For this reason, music wire springs must be plated prior to use; and they are rarely selected for applications where soldering will be done to the probe itself, or where the probe will be used at very high temperatures. The finest diameter springs, however, often must be made from music wire, with few practical alternatives.

Springs that are to be used in highly corrosive or high temperature environments will often be made from stainless steel wire. Stainless steel is also less magnetic. It offers the highest temperature rating of the common spring materials. For these reasons, stainless steel is often employed in connector probes that will be soldered into their final application. To protect the generality of a spring contact probe design, probe engineers will often select stainless steel where required forces and deflection ranges allow.

Occasionally spring designers will use beryllium copper for its excellent fatigue strength. The relatively large wire diameters, combined with the low tensile strength makes it difficult to design springs which are

<table>
<thead>
<tr>
<th>Spring Material</th>
<th>Maximum Temperature (1 Hr.)</th>
<th>Maximum 24 Hour Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Music Wire</td>
<td>250°F (120°C)</td>
<td>185°F (85°C)</td>
</tr>
<tr>
<td>Beryllium Copper</td>
<td>400°F (205°C)</td>
<td>248°F (120°C)</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>500°F (260°C)</td>
<td>356°F (180°C)</td>
</tr>
</tbody>
</table>
small in diameter and high in force with beryllium copper. Springs which are permitted by their application to employ this material are often very long-lasting. The very low resistance of beryllium copper is only a consideration in unusual spring contact probe designs; as will be discussed later, the spring is not normally a part of the current path through a probe, and their resistance is not significant to the probe’s performance.

**Barrels**

The hollow housing of the spring contact probe is generally produced by one of two means. A preferred method is referred to as “deep-drawing”; this involves punching discs of metal into tubes through a progressive stamping process. In this process, the material becomes somewhat work-hardened; the resulting parts are typically very smooth and regular in surface finish, as well as being very concentric. It is easy to achieve fine wall thicknesses with this method and still produce a robust part. Additional features formed in the tube such as press rings, flares, and reductions in diameter must be of a rounded shape; sharp edges are difficult to achieve. Also, these features must not depart too dramatically from the diameter of the main tube. For this reason, deep-drawing is less appropriate when a probe must have a flange for PCB mounting.

Appropriate materials for deep-drawing include brass, phosphor bronze, stainless steel, beryllium copper, and nickel silver. Nickel silver is an extremely ductile cupro-nickel that lends itself particularly well to the deep-drawing process. Because of its high nickel content, it is somewhat resistant to corrosion and can in some circumstances be used without plating. Beryllium copper produces the best electrical characteristics for most applications, although the resonance properties of phosphor bronze have led some designers to use it in probes for extremely high frequencies.
A deep-drawn barrel may be plated in a conventional barrel plating process. It is standard practice to apply a nickel barrier layer of considerable thickness (typically 1-2 microns) before applying secondary, noble metal platings. Gold plating is the most common final layer, at thicknesses ranging from 0.1 to 1 micron. Alternative final layers include palladium, silver, and several other more exotic metals. Most metals are electroplated using conventional techniques; the electroless process is the preferred method of plating nickel. For some applications, an unplated probe barrel is an acceptable alternative. Unplated nickel silver will oxidize over time, and resistance levels for probes made with such barrels will be higher and more irregular, particularly if the probe is not actuated frequently to wipe away the oxides.

A relatively long tube of relatively small diameter poses a challenge to conventional barrel plating techniques. A hole must be created in each end of the barrel to allow the plating solution to flow through the tube and deposit gold and nickel appropriately. In some applications, such as when the probe is to be soldered to a PCB, a hole is undesirable as it will allow solder or other contaminants to penetrate into the spring cavity. A relatively heavy deposit of plating is required on the outside of the barrel to guarantee coverage of its inside diameter, particularly towards the longitudinal midpoint of the barrel. The coverage (thickness of plating) on the inside of the barrel will be irregular.

While variations on the basic barrel plating technique exist which can mitigate these factors, “pre-plating” offers what in some cases is a better alternative. Pre-plating involves covering one or both sides of the base material with precious metal prior to drawing it into a tube. In the process of drawing, the precious metal is stretched, smoothed, and work-hardened. It produces a superior surface finish and very even coverage. In most
cases, pre-plating adds considerably to the cost of the tube in question, and it is not a practical technique for all applications. However, particularly for small diameter or closed tubes, it is the best possible way to provide consistent precious metal coverage of the barrel.

In the event that the application demands square or irregular features on the barrel, or in cases where the barrel is physically too small to deep-draw, machining the barrel is the normal alternative. In a machining operation, the part is turned and milled from bar or wire stock on an automatic lathe often referred to as a screw machine. The lathe may be CNC or cam-controlled. Machining can produce inexpensive parts in many cases, without quite as much tooling as might be required for deep-drawing and without the relatively large minimum order quantities that are associated with deep-drawing. However, the production rates and therefore capacity of deep-drawing machines are generally greater than for screw machines.

Brass, beryllium copper, nickel silver, and phosphor bronze are relatively common material choices for machined barrels. Brass will generally offer the least expensive finished part, while beryllium copper is a good choice for electrical performance. Nickel silver is a bit more machinable, and is therefore sometimes chosen for very small or delicate barrels, or when the barrel will be left unplated. Phosphor bronze tends to have better characteristics when used in high frequency applications. Barrels cannot generally be heat-treated, as this would interfere with the crimp during the probe assembly process. Selective hardening is an option, but can significantly alter the cost of the finished probe.

Machined barrels must be plated by some version of the barrel plating process, as they cannot be pre-plated. For this reason, a plated machined barrel must either have a weep hole to allow plating solution to flow through, or must be of an extremely limited aspect ratio (length to
diameter). Plating material choices for machined barrels are much the same as those for drawn barrels.

**Plungers**

Plungers are normally produced using screw machines. Material choices are the same as discussed under machined barrels, with the addition of tool steel for the preservation of sharp tips. Plungers are almost always heat-treated, to lend structural strength and sharp edge integrity.

Platings for plungers range from nickel alone, in cases where extreme economy is desired, to heavy gold plating. Alternative platings include rhodium, palladium, and other noble metals. Proprietary platings include “Duralloy™,” a silver-colored finish that is very smooth and hard.

<table>
<thead>
<tr>
<th>Comparison of Plunger Plating Characteristics</th>
<th>Gold</th>
<th>Nickel</th>
<th>Duralloy™</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistivity (W cir mil ft)</td>
<td>11.4-28.9</td>
<td>181.5-331.0</td>
<td>64-90</td>
</tr>
<tr>
<td>Hardness (Knoop)</td>
<td>160-190</td>
<td>500-600</td>
<td>930-1100</td>
</tr>
<tr>
<td>Hardness (Rockwell B)</td>
<td>78-86</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>(Rockwell C)</td>
<td>—</td>
<td>47-53</td>
<td>&gt;68</td>
</tr>
<tr>
<td>Tensile Strength (ksi)</td>
<td>16-31</td>
<td>100-122</td>
<td>101-112</td>
</tr>
</tbody>
</table>

**Lubricants**

Lubrication is more common in probes that are designed for test applications, where cycle life is a primary design characteristic. Lubrication, while in many cases beneficial to probe endurance, creates problems with dust attraction. In addition, lubrication forms a primary failure mode when probes are used at high temperatures. Probes can typically be designed to give very good cycle life without requiring lubrication.

**Crimping Techniques**

The simplest form of probe crimp is the “roll top” (figure 15a). This style calls for a plunger having a defined
tail. The tail is captured by a crimp at the top of the barrel that is smaller in diameter than the plunger tail and larger than the plunger shaft. The plunger shaft passes freely through the crimp. Roll-top probes make the best use of probe internal space, and are appropriate where a large spring cavity is desired. Roll-tops do not inherently control the radial deflection of the plunger, and are usually kept out of contact with the plunger shaft.

“Center crimp” (figure 15b) probes have an extra step in the plunger referred to as the “minor diameter”. The crimp still captures the tail of the plunger, but it is moved closer to the midpoint of the barrel. The minor diameter passes through the crimp, and probe travel is often stopped by the change in diameter of the plunger from minor diameter to plunger shaft. Center crimp probes have a very long plunger bearing surface by nature, and are therefore often better at controlling radial deflection of the plunger at the expense of available spring cavity. They also present a larger diameter at the
point where the plunger shaft exits the barrel, and for that reason are sometimes more robust than roll top probes.

Center crimp probes may be modified by having the top of the barrel formed to a closer fit around the plunger (figure 15c). Because of metal spring-back, a gap will remain around the plunger even if the plunger is used as a mandrel for this forming process. However, that gap (working clearance) can be reduced to half of its nominal condition in many cases by this technique.

Roll-top probes may be similarly modified (figure 15d) by moving the crimp below the top of the barrel. A second crimp may then be applied to guide the plunger. The same limitations on the tightness of this crimp apply.

Native Applications

Spring contact probes were originally developed for test applications within the industry of printed circuit board manufacturers. Probes are arrayed in fixtures in a manner that mirrors the pattern of points that are to be contacted on the printed circuit board under test. Wires are attached to the receptacles of the probes that allow the probes to be connected to a tester. The printed circuit board to be tested is pressed against the spring contact probes (figure 16).

By compressing the printed circuit board against the spring contact probes, each probe tip is brought into
contact with the test point on the printed circuit board. In this manner, spring contact probes are used to adjust to z-axis variation in the contact topography of the device under test (figure 17). Printed circuit boards or semiconductors, or any number of other electromechanical devices may be easily and quickly connected to a testing apparatus. This allows printed circuit board manufacturers to test one hundred percent of their output, not once, but repeatedly after different stages of manufacturing.

Later, spring contact probes were refined to the point that they could be used to test semiconductors. Because of the compact nature of these test targets, wireless interconnection came to be accepted as the best way to interface the tester to the spring contact probe fixture. This led to the development of double ended and “floating” interposers.

**DC Electrical Characteristics**

The preferred electrical current path through a spring contact probe begins at the plunger. The plunger is typically a relatively bulky machined piece plated with precious metal, and as a result, will normally have very low resistance. In an average-sized spring contact probe, that value might be roughly 5 milliohms. The current then has
the opportunity to make a transition to the spring or to the barrel. The barrel is likely to have a resistance similar to that of the plunger; the spring, on the other hand, is a long thin piece of metal, and as a result, has a basic resistance of an Ohm or more. For this reason, the current will follow the most direct path from the plunger to the barrel.

From there, it passes via the detent to the receptacle (if applicable) and then to the wire joint (see figure 18). If a double-plungered probe is employed, the current must pass instead to the secondary plunger, before flowing to the printed circuit board.

The basic resistance of the probe is very low, typically only a few milliohms. However, there are at least two points of contact resistance which are much more significant, and more variable.

There exists contact resistance between the plunger tip and the contact surface that forms its target. This resistance varies with the amount of penetration the plunger tip has into the contact surface, through whatever nonconductive materials (such as oxides or debris) that exist. A greater surface area of contact between plunger and target, whether established by penetration of the tip into the contact material (figure 19a) or by conformance of the contact material to
the tip (figure 19b), will result in less constriction resistance and thus less contact resistance. This will vary with the sharpness of the tip, the amount of compression force delivered by the probe, the degree of contamination of the contact surface, and the material characteristics of the contact surface such as hardness and nobility.

There remains to be considered the contact resistance between the plunger(s) and the barrel. Extremely linear compression of most conventional spring contact probe designs will result in very limited contact force between these two elements (figure 20). This phenomenon is known as “centering.”

Fortunately, to some degree, most spring contact probe applications do not feature a perfectly linear compression vector. The target is often presented at a slight angle or with a non-axial compression vector, causing radial deflection of the plunger during compression. This condition might be described as a state of “sideload” (figure 21).

In such circumstances, the plunger will be driven into a more secure contact with the barrel. As greater force is exerted in a non-
axial direction on the plunger, the plunger and barrel will be forced into greater conformance with each other, creating a larger current path and thus generating less constriction resistance.

Contact from the plunger to the target may be reliably established by selecting the appropriate tip configuration and spring force. Once this is established by design and proven in fact, it will tend to remain fairly consistent as the variables affecting this contact are somewhat fixed. With appropriate selection, this contact resistance value can be minimized as well as controlled; in optimal conditions, it may add as little as a milliohm to the total circuit.

In the past, contact from the plunger to the barrel tended to vary tremendously if not carefully controlled. The vector of compression was challenging to predict and even more difficult to fix. For this reason, contact resistance between the barrel and the plunger added significantly to the circuit and did so in an intermittent fashion; this caused many applications, such as the charging of a battery in a portable device, to fail on an unpredictable basis.

Fortunately, probe design engineers have created a number of devices for ensuring good contact between the plunger and the barrel. Most of these employ some means of “biasing,” or causing the plunger to tilt within the barrel by mechanical contrivance.

The oldest biasing technique, patented in 1969 and now public domain, is referred to as the “bias ball” (figure 22). A bias ball probe construction involves a plunger with an angular face on its tail. A metal ball is interposed between the plunger and spring. The ball acts as a fulcrum and the angle as
a lever, causing the plunger to tilt radically within the barrel. This is the most aggressive biasing technique, and as such is typically the most successful in controlling internal contact resistance during the initial life cycle of the probe. Because this biasing technique is so forceful, it causes rapid wear on the plating surfaces of the probe; as a result, resistance begins to rise and become more intermittent as the probe is cycled. While this can be limited with careful material selection, this technique is best suited to applications requiring a relatively small number of cycles (less than 50,000 in the most aggressive designs). The ball also takes up valuable “real estate” within the probe, limiting either the available bearing surface for the plunger, the spring cavity, or the overall compactness of the probe as discussed earlier. Additional expense is also associated with the inclusion of an additional probe component, as well as with the unusual machining techniques required to cut an angle on the tail of the plunger. Finally, since the angle on the tail is fixed in orientation, the wear on the surface of the plunger shaft will always follow a fixed track. Because of this, the plating on that surface tends to wear away particularly quickly, and in extreme cases a hole will be worn in the barrel.

A subtle variation on the bias ball design is the “bias plunger” technique (figure 23). Made possible by advances in coil spring manufacturing techniques, the bias plunger design reduces the severity of the angle on the plunger’s tail, eliminates the ball, and carefully closes the ends of the spring to ensure good mating with the plunger. The bias plunger shares the advantages and disadvantages of the bias ball design, better consistency of resistance, coupled with rapid wear and some level of expense, to a lesser degree.

Fig. 23
Bias Plunger Design
The bias spring design (figure 24) uses a conventionally wedge-shaped plunger tail. The spring is cigar-shaped, tapering at each end. The small, closed coils of the spring cause the plunger tail to seat poorly. As the plunger is compressed, the spring causes the plunger tail to angularly deflect. This is the least effective biasing method in terms of lowness and consistency of resistance. However, it is also the kindest to the probe mating surfaces, and wear is much less aggressive than with the other bias designs. Since its bias technique does not have a fixed orientation, plunger wear tends to be more evenly distributed. Further, the bias spring does not change the overall cost structure of the probe.

The above techniques are widely practiced throughout the spring contact probe industry. There do, however, exist two techniques for probe construction that are proprietary to a single vendor. The “bifurcated probe barrel” (figure 25) effectively obsoletes biasing techniques where applicable. It is possible to split the top of some types of probe barrels and form them tightly against the plunger. The probe barrel, by virtue of the split, behaves much like an array of leaf springs. This compliance allows the probe designer to create an interference fit between the probe barrel and plunger, with the plunger very nearly centered in the barrel. The plunger-to-barrel interface is a wiping contact around nearly the entire circumference of the plunger. This eliminates the inherent angular deflection of the bias designs, and thus their tendency to introduce accelerated wear. Electrical resistance is lower and more consistent with this technique than with any of
the others so far shown in Chart A. At the same time, pointing accuracy is greatly increased (Chart B), resulting in the ability to use smaller contact pads. Finally, the probe is effectively sealed against contaminants, adding to probe reliability.
The bifurcated barrel is a tooling-intensive technique, with significant development time required for any new application. It is only applicable to certain barrel types and materials. However, it has been shown to be dramatically effective where employed, and is used in many high-performance connector applications.

A more radical approach to basic probe design is the patent pending “capsule probe” (figure 26). This concept involves a probe barrel that houses a hollow plunger. Much of the spring cavity is effectively resident inside of the plunger, and as a result the ratio of probe overall length to deflection range is better than any other type of probe. This is useful for RF applications and other applications calling for very short probes. The highest bandwidth and lowest inductance non-coaxial probe designs are capsule probes.

Further, the extra room granted by the hollow plunger allows capsule probes to feature a tremendous amount of bearing surface. As has been discussed, probes with extended bearing surfaces feature increased guidance for the plunger and work harder to overcome radial deflection. This makes a degree of control normally found only in much longer probes available in the compact designs appropriate to RF and low profile connector applications.

However, this increased bearing surface contributes not only to the smoothness of actuation of capsule probes, but to their electrical performance as well. Because it must fit within the relatively small cavity of the plunger, the spring is smaller and therefore less guided than in other probe designs; as the x-ray photography in figure 27 illustrates, this causes the spring
to snake within the barrel and plunger. As a result, the plunger is forced to shift axially rather than deflecting radially if the probe is properly designed. The axial shift brings the entire side of the plunger into contact with the barrel, rather than just the corners of the plunger.

For this reason, the contact resistance within capsule probes is very low. Low internal contact resistance is welcome in any high performance probe design; however, in the RF applications, capsule probes are suited particularly well because of their shortness and the easy transfer of power, within the probe, limits the noise generated through the transmission lines. The best bandwidth results obtained to date with non-coaxial spring contact probes have come with the advent of the capsule probe design.

The most successful capsule probe designs to date have been made using deep-drawn tubes for both halves of the probe. The very thin walls created in the deep-drawing process lend themselves to creating maximum capacity within the capsule probes. The smooth surface finish inherent in drawn components assists the large contact path that contributes to their low contact resistance. The pre-plating techniques possible with deep-drawing simplify manufacturing considerably. However, as mentioned, deep-drawing can only produce relatively rounded shapes; the large square-edged flanges and complex contact geometries desirable in many applications are difficult to achieve. It is possible to embody the capsule probe concept in a probe that has one or both components machined, but sacrifices must be made in internal capacity and surface finishes and tolerances must be very carefully controlled (figure 28).
High Frequency and Controlled Impedance Designs

Increasingly, the integrity of high frequency signals passing through spring contact probe connectors is a primary consideration. In some cases, it is critical that the signal maintain its native impedance through the connector, mandating some method of controlling that impedance. In others, it is desirable that the signal encounter minimal loss or inductance while traveling through the connector. In response to this, probe designers have created several different approaches for dealing with high frequency and controlled impedance applications.

The fundamental problem with spring contact probes as high frequency transmission lines is their length. Most probes are designed to have a fairly significant amount of compliance, and prior to the emergence of signal integrity as a concern, it was rare to find spring contact probes less than 10 mm in length. Signals passing through unshielded transmission lines of such lengths at frequencies in the RF range tend to experience too much loss to be useful.

![Chart C: Bandwidth of LCR100](image)
The development of very short spring contact probes, such as the capsule probes discussed previously, allow much better performance with regard to both loss and impedance control. A sufficiently short transmission line will allow the characteristic impedance of one member of the interconnection to overlap with that of the other. As a result, reflections due to changes in signal impedance are minimized. Further, very short spring contact probes minimize inductance, in many cases well below 1 nH. Loss is minimized, permitting bandwidths well above 10 GHz for some designs (Chart C).

Where the interconnected members feature poor positional tolerance or coplanarity, very short probes will not have sufficient travel to allow for secure contact. In such applications, probes perform best when placed in controlled impedance environments, particularly if the impedance of the transmission line is matched to that of the two elements to be interconnected.

Techniques for producing controlled impedance with spring contact probes can be divided into two types: those which use a common ground element to shield the spring contact probes, and those which permit the transmission of discrete ground from one half of the interconnection to the other.

Where common ground is permissible, a spring contact probe may be made coaxial by simply installing it in a grounded block, separated from the block by an insulator. Spring contact probes are then installed directly in the block to draw ground from the unit under interconnection. The block shields the signal passing through the spring contact probe. The dielectric properties of the insulator used and the distance between the spring contact probe and the shielding block determine the impedance of the transmission line. It is possible to use air for the dielectric insulator by suspending the probe in the block with short washers or a keeper plate; this allows the highest density
and in many cases the best RF properties (figure 29). With this methodology the signal is unshielded only where the probe extends from the face of the block at the target and termination ends.

An individual tube may be used to contain the dielectric insulator (Figure 30). In this construction, it is easier to shield the probe if terminated to coaxial cable. The coaxial probes are mounted in a conductive block.
with ground probes, or in an insulative block with an arrangement to short the ground probes to the shielding tube (figure 31).

If a probe with an individual tube is used, it is possible to keep the ground for each signal discrete. While coaxial probes may be tied to ground probes individually as described above, this arrangement is somewhat cumbersome to manufacture, and the problem of unshielded probe extension from the tip of the block remains. Patented designs exist, however, which utilize a concentric shielding plunger (figure 32). The target for such a probe, most frequently a pad on a printed circuit board, may have a matching annular ground land to make full concentric contact with the shielding plunger. Signal is brought to this pad arrangement through a via in the center of the ground land.

**Conclusion**

Spring contact probe design is a relatively exhaustive subject. A deep understanding of metallurgy, DC and RF electrical behavior, and complex mechanical principles is displayed in the thousands of patents that decorate the short history of this technology. However, it is the constant investment of innovation that has made spring contact probes infinitely useful as a connector technology, as will be detailed in the chapters to follow.
Contact Technologies

Connectors employing spring contact probes can significantly improve the performance and manufacturability of a wide range of products. Of course, probes are not always the best possible choice for every application.

This section describes competing connector technologies. It contrasts them with spring contact probes and with each other in relevance to certain very general characteristics. This will allow the reader to understand the general benefits and limitations of spring contact probe connectors within the context of existing solutions.

The third section of this book will examine some specific examples of applications where spring contact probes have proven to be the best possible choice for a particular interconnection. In doing so the connector selection process used by the design engineers of these products will be exposed, and the advantages of probe-based connectors will be more concretely discussed.

Comparative Survey of Contact Technologies

Connector specifiers select from a blinding array of contact technologies. Each of these differentiates itself from its competitors by doing some things (or, in some cases, one thing) particularly well.

Two predominant choices in core technologies lie at the heart of most of today’s connectors: bent metal and pin-and-socket contacts. Like the spring contact probes discussed earlier in this book, each of these technologies comes in a wide variety of shapes and sizes, with various levels of differentiation. However, these two general categories cover the majority of existing designs.

Bent Metal Contacts Vs. Spring Contact Probes

Bent metal contacts (figure 33) are relatively fine pieces of metal formed into a curvilinear shape in order to provide a cantilever effect that grants them compli-
ance. These contacts are normally then insert-molded or stuffed into a non-conductive carrier of some sort. A portion of the contact protrudes beneath the carrier for attachment to the PCB by surface mount or through-hole interconnection. Bent metal contacts can also have a compliant form on both ends to provide for solderless interconnect.

Like spring contact probes, bent metal contacts are typically designed to target a pad on a printed circuit board, or a hard flat metal contact mounted on a PCB. This is a major advantage, as the mate for either a bent metal or spring contact probe based connectors can be made very inexpensive in contrast to those technologies that demand a specialized secondary component.

Thus, bent metal contacts can offer as many application alternatives as can connectors made from spring contact probes, both in terms of the variety of interconnection styles and in terms of the types of targets suitable for use. However, bent metal finds its limitations in specialization.

Bent metal contacts are typically stamped from a fairly elastic metal such as beryllium copper. They are plated if necessary, for electrical contact enhancement and corrosion protection. However, they may be manufactured by less tooling-intensive or shape-limiting technologies, such as electroforming or chemical etching.

The stamping process is causative to both the greatest advantage and the greatest disadvantage of bent metal contacts from a manufacturing perspective. Because stamped parts are extremely inexpensive when produced
in large quantities, bent metal contacts are typically one of the lowest-cost solutions available to a design engineer. In many cases more cost is associated with assembling the contacts into their carrier than in producing the contacts themselves. Depending on pin count, connectors employing bent metal contacts may be less expensive by an order of magnitude than probe-based solutions — but this is true only with off-the-shelf designs or in very high volume custom applications.

Because stamping and molding are very tooling-intensive, connectors based on bent metal are normally a good choice only when produced in very large volumes. Custom applications at medium volumes are ill-suited, and prototyping during the design phase of even a large project can be prohibitive. As a result, development of a new or innovative connector design using these technologies demands serious commitment, and smaller-volume or faster-paced projects are often limited to off-the-shelf solutions.

By contrast, spring contact probes can be custom-designed and prototyped in very low volumes rapidly and cost-effectively. Many of the early applications of spring contact probe-based connectors were motivated strictly by this feature, as spring contact probes allow the user to produce cost-effectively even at start-up or exploratory volumes.

Bent metal contacts normally employ a wiping or scrubbing motion, moving laterally upon compression, both as an inevitable result of their compliance and in an attempt to establish positive contact to the target. Wear of both the contact and the target is exaggerated, and contact resistance gradually rises and becomes increasingly unstable over a number of cycles. For this reason, insertion life of bent metal contacts is typically measured in the hundreds or low thousands.

In this sense, bent metal contacts are vastly inferior to
probes. Even poorly designed and cheaply manufactured probes will outlast, by an order of magnitude, the average bent metal connector. For any application requiring contact reliability over medium or high cycles, spring probes provide an immediate return on their elevated cost, and are normally a superior choice.

Bent metal contacts generate their compression force on a curve. Forces build geometrically as the cantilever is buckled through its range. If the designer at a nominal amount of compression selects a given force, the “preload” force of the contact must be radically lower. For that reason, bent metal often does not generate enough force to make reliable contact until after it has been significantly compressed. Spring contact probes, however, use coil springs. Coil springs build force linearly, which means that relatively high preload-to-rated-force ratios can be produced. Spring contact probes provide sufficient force for contact within a wider amount of their compression range than do bent metal contacts, and therefore accept a wider range of manufacturing tolerances of the parts to be connected.

A moderately wide range of contact force may be designed into bent metal contacts. However, each insertion cycle encountered by the contact exposes it to fatigue. Thus, the contact force of bent metal gradually declines. Therefore, the contact resistance of bent metal contacts would continually increase over cycle life, even if contact and target wear was not a concern.

By contrast, spring contact probes are normally based on coil springs, which retain more or less their initial force throughout their entire mechanical life. Again, high reliability applications would lean toward spring contact probes, as would those applications where force of contact is critical for mechanical reasons.

The same dependence on metal memory that makes fatigue life a concern also defines the temperature range
at which bent metal contacts may be used. Temperatures outside the limits of beryllium copper will cause it to stress-relax, making the contacts noncompliant. Because coil springs can be made out of a wider variety of materials, they are not nearly so limited in this regard, and can be handled more easily during the soldering process as well as being employed in a fuller range of applications.

Bent metal contacts can be compressed extremely flat, and can be made to fit on very fine pitch. In many cases, this makes them suitable for compact applications. However, the compliance of bent metal contacts demands that they take up a significant amount of room in one axis, and the pitch of a bent metal array may be limited to one or two lines of contacts. Bent metal contacts almost always have a relatively long signal path if they provide even a minimal amount of compliance, and are thus a relatively poor choice for RF applications.

Spring contact probes are capable of approximately the same pitch range as bent metal, but are columnar. In this sense, they take up much less PCB ‘real estate’ in the X and Y axes than bent metal contacts (figure 34). Further, their signal path length can be made to be extremely short, making them suitable for RF applications.

While the cost-effective employment of off-the-shelf or high volume bent metal contact technologies should allow them to continue to be one of the default connector technologies for most applications, their limited reliability

Fig. 34
Top View of Space Requirements
and comparatively narrow application range makes them a second choice to spring contact probes in high performance applications. Further, the inflexibility of their manufacturing process makes them less useful as products are developed with less time-to-market and in lower, more exploratory volumes.

**Pin and Socket Contacts Vs. Spring Contact Probes**

Pin-and-socket is perhaps the oldest and most basic type of connector technology. This generic term refers to any connector scheme wherein a male plug is inserted into a female receptacle or jack. Typically by some form of wiping mechanism, the pin makes a press-fit into the receptacle, and thereby derives its electrical contact; this also creates a certain amount of withdrawal force for the pin.

This last element points to the primary difference between bent metal (and probes) and pin-and-socket connectors: pin-and-socket schemes have the virtue of withdrawal force. Bent metal and probes (and several of the other technologies discussed below) have ejection force, rather than any sort of inherent retention force. If a connector is designed using ejecting contacts, some secondary latching mechanism is necessary to hold the connector in place. With pin-and-socket connectors, the connection is retained until forcefully withdrawn.

Nonetheless, designers using pin-and-socket based connectors typically incorporate additional retention features, as the withdrawal force of the pins from the sockets in the connectors may not be enough to grant significant security of connection in the final application. In light of this, it is relatively easy to grant the inherent retention of pin-and-socket connectors too much significance.

In their simplest form, pin-and-socket connectors simply use stamped pins and receptacles, with detents to accomplish the wiping contact necessary for their electrical contact and retention. These are typically limited to hard-
wired applications, but are common in many industries, such as in the case of automotive and telecommunications connectors. However, these connectors have very short cycle lives, as well as the same limitations as stamped bent metal contacts in regard to product development and design flexibility.

Alternative pin-and-socket connectors are available with a wide variety of wiping contact inventions, which controls their reliability and performance. Complex, expensive pin-and-socket connectors are available which employ a wire mesh that tightens as the pin is inserted. These are very effective electrically, but are expensive and limited to fairly gross sizes and wide pitches. A common type of pin-and-socket connector uses a beryllium copper basket to wipe against the male pin; again, cost and size are limiting factors. One last technology, often referred to as a “fuzz button,” employs a loose fibrous matrix of very fine gold plated beryllium copper wires stuffed into a shell. A male pin is pushed into the fibrous matrix, and establishes contact in this manner. Because the “fuzz button” has a very large area of positive contact with the male pin, electrical properties are usually good and connection is very reliable. Also, since the fibrous matrix is compliant, the “fuzz button” features ejection force rather than withdrawal force, more like a spring contact probe or bent metal connector. However, the fibrous matrix tends to wear quickly, with the pin making a hole and lessening contact effectiveness over the course of hundreds of cycles. Once more, the machined shells into which the “fuzz buttons” are placed limit this technology.

All of the above technologies are exclusively through-hole or hard-wire mounted, and both use heavy screw-machined shells that compare poorly to stamped contacts for ease of mass production. The limited mounting options available with pin-and-socket connectors often make them cost even more to employ in a product than their actual
worth, which is already on par with spring contact probes.

Further, these connectors are not compliant in the normal sense; the pin may be inserted to various depths, but a blind mate, whether in application or in the assembly process, is not necessarily reliable or assured. This adds to the complexity of deployment of these connectors within a product, and thus to their inherent cost.

Pin-and-socket connectors by nature have a very long signal path. They are difficult to use in compact applications and when they will be used for RF applications they must be made in a coaxial, shielded format. This adds tremendously to both their cost and to the difficulty of achieving a blind mate.

Spring contact probes are available in finer pitches than pin-and-socket technologies. They can be made with much shorter signal path lengths, granting coaxial performance without coaxial costs. Probes are fundamentally simpler than pin-and-socket solutions, when the added complexity of the mating half is considered. Probes are much better suited to blind mating than pin-and-sockets, particularly on fine pitches. Lastly, probes typically offer far more mating cycles than pin-and-socket connectors, as pin-and-socket is still reliant on the same wiping contact that is the downfall of the bent metal connector.

**Conductive Elastomers Vs. Spring Contact Probes**

Naturally, other technologies have arisen in parallel with spring contact probes to combat the weaknesses inherent in bent metal and pin-and-socket connectors. However, these connectors are useful only in a limited range of applications, and have not found wide adoption.

An interesting variation on bent metal concepts is the range of products known typically as conductive elastomers. Conductive elastomers consist of embedded conductive components within a compliant medium. This may be carbon or silver, for example, where it is desired
for the entire conductive sheet or column to be common. Alternately, it is possible to make “z-axis only” conductive elastomer, which typically has beryllium copper wires suspended vertically in the compliant matrix. The wires are separated from each other by the insulative compliant compound, and buckle when compressed.

Conductive elastomers feature very short signal paths, and thus have great potential for RF applications. The wires are on very fine pitch, and it is possible to have very dense arrays of interconnections. Further, the elastomers have no inherent personality, and can be die-cut to shape and used in almost any application. They require relatively little in the way of specialized mating surfaces—gold pads on a printed circuit board are ideal—and thus can be very cost-effectively employed in board-to-board applications.

However, conductive elastomers, whether common or “z-axis only,” have several serious limitations. The compression force required to gain any reasonable amount of compliance and also to generate sufficient electrical performance is much higher than that required for any other technology. Conductive elastomers must generally be compressed up to 20% of their overall height to provide the best possible electrical path. The amount of force necessary to do this depends on the surface area of contact; an array with a number of interconnections could easily demand forces more than 10 times that needed to compress a spring contact probe.

Further, since conductive elastomers are effectively common mechanically, they are subject to a phenomenon which might be described as “mechanical cross-talk.” Compression of the elastomer at one point raises the force necessary to compress neighboring points. This is grossly compounded if the deflection is angular—for example, when the mate is compressed against the elastomer with a rocking or nonlinear vector. This can make the forces required to compress the elastomer extremely difficult.
to predict, compromising performance in application. Spring contact probes, by contrast, are mechanically self-contained. Compression force is absorbed entirely by the spring, which prevents variation caused by the performance of neighboring contacts.

Properties of Contact Technologies

In this section some basic properties of the various contact technologies are compared. Where possible, multiple embodiments of a given technology (for example, one vendor’s modular bent metal contacts and another’s customized bent metal contact assemblies) have been represented. The data used for this comparison is based upon extensive internal testing and those companies’ own reports.

![Comparative Contact Resistance](image)

Figure 35 shows the average contact resistance for a nominal, comparable size and pitch of contact. This characteristic determines various things about the predictable performance of these contacts, most particularly for DC
applications. As one can readily see, spring contact probes fall squarely in the middle of the available technologies. Wire sleeve contacts provide very good contact resistance values, consistent with field experience; stamped metal pin-and-socket connectors also do well. Conductive elastomers and bent metal contacts do poorly, because of their relatively high inherent resistivity – the metal content of conductive elastomers is fairly low, and bent metal contacts are made from relatively thin pieces of metal.

![Comparative Current Capacity](image)

Figure 36 is interestingly in opposition to conclusions that might be drawn from the comparative contact resistance of the various contact technologies. Wire sleeves, for example, provide good contact resistance, and might be assumed therefore to have the best current carrying capacity. However, it is important to note that many of these technologies carry current through their compliant motive drivers (figure 37). As a result, high amperage
causes excessive heating at mechanical points vulnerable to stress relaxation. Properly designed spring contact probes can carry far higher currents than the other technologies, on comparative densities, because the compliant driver is separated from the current path — flow is from the plunger to the barrel, avoiding the spring. Current capacity as shown in the graph (figure 36) is even possible with probes only 2.5 mm long and 0.3 mm in diameter. Larger, bulkier probes can be made with many times this capacity.

Maximum density is a fairly evolved property — most of the designs in circulation have been compressed over time to their bare physical minimum. Conductive

![Diagram](image-url)
elastomers can be made to have very fine conductive matrices, but it should be noted that the vertical wires that carry signal through the elastomer will eventually break down over cycle life and begin to short. As previously noted, pin-and-socket connectors are limited by their machined shells and through-hole or hardwired design to a certain minimum practical pitch (figure 38). While the minimum pitch for bent metal contacts can be reduced to minimal numbers, it must be remembered that since bent metal requires a non-axial deformation space, only one or two rows of contacts can be placed on the listed pitch. Spring contact probes, being columnar, can be placed on a full matrix, allowing for maximum densities. Extruded and machined barrels can be made to very small diameters, and so spring contact probes provide the finest density available without resorting to conductive elastomers.

The similarity in the various technologies’ operating temperature ratings is due to their dependence on beryllium copper or similar materials for their compliant force (figure 39). Beryllium copper stress relaxes when exposed to temperatures exceeding 125° C, losing its force and taking a set. Conductive elastomers can suffer from a failure of their elastomeric compounds at even lower temperatures.

![Operating 24-Hour Temperature Range](image-url)
Further, their conductive materials move too far apart under thermal stress to provide reliable electrical performance. Spring contact probes can be made with stainless steel springs, which allow a 180°C temperature rating for 24 hours. Exotic coil spring materials such as Inconel can expand this rating significantly.

While the various pin-and-socket technologies provide acceptable cycle life for most applications, no contact technology in widespread usage can match the insertion life offered by spring contact probes (figure 40). This is due to the extreme reliability of helical compression springs as compliant members. The buckling beams of both bent metal and conductive elastomer technologies inherently overstress the materials critical to their performance. The wiping action of bent metal further eradicates their potential for high numbers of insertions. In applications demanding contact reliability over a high number of cycles, spring contact probes often emerge as the only viable connector technology.
The available range of forces within common sizes again illustrates the superiority of the coil spring as a compliant technology (figure 41). Bent metal, by nature, generates force from one single bend in the compliant beam. Since that bend must bear the entire force of compression, the amount of force that can be designed into bent metal is limited by the material strength of that beam. Spring contact probes take advantage of the nature of coil springs, which spread the stress of compliance out over the entire helix. Therefore much higher forces can be produced with finer materials without compromising the reliability of the connection. The very high compression forces required for conductive elastomers are well illustrated here; the data presumes a single compression point, which is an unlikely application of this technology.

One of the more important characteristics to consider when selecting contacts for compact applications is the amount of compliance available with a given contact technology in relevance to its overall open

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<tr>
<td>Bent Metal</td>
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<td>Spring Contact Probes</td>
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<td>Conductive Elastomers</td>
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Fig. 41

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<th>Relative Compliance-to-Length Ratio</th>
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<tr>
<td>Compliance</td>
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<td>Conductive Elastomers</td>
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Fig. 42
length (figure 42). In a compact application, it is critical to remember that while short contact length may be greatly desirable, the connector must still have enough compliance to guarantee contact over the entire range of possible mating components. Pin-and-socket contacts naturally are exempt from this consideration; overall length of the contact when engaged is equal to the length of the female receptacle, effectively granting a 1:1 ratio in this sense. Conductive elastomers and “fuzz buttons” used outside of a containing shell offer very poor ratios of length to compliance, due to basic physical limitations of their respective compression technologies. Since bent metal compresses in a non-axial manner, they also are capable of near 1:1 compression ratios; however, it is critical to remember that these contacts must take up that same amount of room in some axis, and in net effect bent metal often does not offer the same compactness as its ratios might suggest. Spring contact probes can be said to offer the greatest ratio of all of the technologies that can simultaneously achieve a dense, fine contact matrix.
Examples of Spring Contact Probes in Connector Applications

Example 1: Spring contacts for antenna interconnection in a cellular phone.

Cellular phone handsets represent one of the most popular and exciting consumer electronics products currently manufactured. Performance, size, manufacturing costs and time to market are incredibly important considerations for cell phones, and innovations are surfacing from all related industries as a result.

Our first example of a spring contact probe-based connector comes from this dynamic industry. Somewhat unusually, this application does not take advantage of the spring contact probe’s well-known forte, its long cycle life. Instead, probe-based connectors are being designed into cell phone applications based on their reliability of contact, RF performance and columnar shape.

Specifically, spring contact probes are being heavily used to interconnect the main printed circuit board of a cellular phone with its antenna. This interconnection must carry a signal equal to the reception frequency of the cell phone (frequently as high as 2.4 GHz). It is normally accomplished with a small pin-and-socket style coaxial connector, which is soldered in place on the phone board, and a mate to which the antenna is terminated. During the assembly process for the handset, the antenna is snapped into the connector on the printed circuit board, and then the remaining elements of the cell phone’s handset are assembled.

The pin-and-socket based coaxial connectors employed for this are a relatively costly component. In an effort to cost-reduce these connectors as literally millions of them are consumed annually, the cell phone manufacturers have in fact driven some of the reliability out of what were originally very high performance connectors. The incidence rate
for intermittent connection of these two critical components has risen in some specific cases far beyond what the cell phone manufacturer considered acceptable. This is a particularly troublesome manufacturing defect, since often a partially-plugged pin-and-socket connector will test well at the factory and then fail when exposed to shock and vibration in the field.

Further, the connectors require placement and soldering to both the printed circuit board and the antenna. The labor involved in this technique is both cost significant and fault prone. Placement of the connectors is difficult to integrate in an otherwise automated production line, and the soldering process is critical to their electrical performance.

Initial efforts to integrate spring contact probes in this application proved to be too rooted in the original technology to allow any significant gain in manufacturing performance or reliability. The center signal conductor of the coaxial pin-and-socket connector was simply replaced with a spring contact probe. The shielding contact remained a concentric bent metal shell, which mated with a drawn shell terminal. While signal contact reliability was somewhat improved with this technique, the creation of a customized connector proved more costly than the benefits justified.

![Antenna board and Main circuit board with connectors](image)
It was soon realized that at the lengths required for the Z-axis transfer of signal from board to antenna, the columnar nature of spring contact probes gave them acceptable high frequency performance without coaxial shielding in most applications. Thus, the practice of soldering two relatively short spring contact probes — one signal, one ground — into the printed circuit board and allowing them to contact pads on the printed circuit on which the antenna was built was tested (figure 43). Assembly was greatly simplified through this technique, since a blind mate with spring contact probes is much more easily accomplished than with a pin-and-socket style connector. Contact reliability under conditions of vibration and shock was much improved, since partial mates are both unlikely and well tolerated by spring contact probes. However, placement of the spring contact probes and reliable soldering to the printed circuit board was still an issue.

In some applications, matched impedance was critical to the proper performance of the antenna. Spring contact probes are relatively easy to mount in a matched impedance environment, by installing the probes in a metallized block with the ground probe in contact with the block and the signal probe insulated at a specific distance from the block’s inner walls (figure 44). While the probes used in such applications, designed for surface-mount rather than through-hole interconnection, improved automation integration of this component, the probe-based connector had yet to find its full potential for assembly simplification and cost savings.

As cell phone designers became more comfortable and familiar with spring contact probe technology, the concept of using double-ended probes for the application was explored. Probe connector designers were able to manufacture simple plastic blocks containing two double-ended
contacts (figure 45). The blocks could be plucked from bulk packaging by human hands or from tape-and-reel packaging by robotic assembly machinery, depending on the burden rate of the production location. The blocks are then dropped or fitted into the housing of the cell phone, so that when the antenna is assembled onto the main housing the probes interpose between pads on the antenna and the basic printed circuit board (figure 46).

With this innovation, the cell phone industry has found a way to make an extremely critical interconnection more reliable, at lower component cost, while at the same time greatly simplifying assembly processes. This advance is due to spring contact probes, which are normally famous for being able to withstand hundreds of thousands of interconnections; here, spring contact probes are advantageous due to their ability to make one interconnection cycle very, very well.
Example 2: Spring contact probes for power and data interconnection in mobile radios

Mobile radios, unlike most other examples of portable electronics, see frequent mating and disconnection of the battery and hand-held microphones. Where carried by military, police, and emergency services personnel, the hand held radio is a lifesaving tool, and its reliability is paramount. It is absolutely vital that the battery connection, in particular, not be subject to intermittent voltage drops. These will cause the battery to drain quickly, which can result in a dead radio at a critical time.

For this reason, many manufacturers of mobile radios have chosen to employ spring contact probe based connectors in these roles. Battery contacts, in particular, have been a focus of these manufacturers.

One of the most developed examples of such an application is a three-probe header used as a battery contact in a very established radio design (figure 47). The probes used in this application are designed for the utmost in reliability and low-resistance interconnection. An aggressive bias-ball design is employed, which assures absolute consistency of internal contact resistance (figure 48). This is accelerated, and external contact resistance is controlled, by the relatively high (190 grams at rated travel) spring force of the probes. Through such measures,
the probes typically deliver contact resistances under 5 milliohms, a value that remains constant through 50,000 cycles. As is typical with aggressive bias ball designs, cycle life is limited to this relatively low figure, but this is considered by the specifier to well exceed any possible product application requirements.

A unique feature of this design is its packaging, which is expressly designed for high speed automated production. The plastic header is mated to a solder preform (figure 49) and placed in a tape-and-reel pocket (figure 50). The hole in the header allows a gantry-style robot with a vacuum pickup to pull the probes and preform from the packaging and place them on the board. The solder preform is reflowed to large lands on the printed circuit board in a conventional IR process (figure 51). This allows the holes drilled in the board to be free of internal plating, making their finished size and position much more accurate; the probes receive excellent mechanical alignment in this fashion, and the entire operation may be easily integrated with a high-speed SMT line.

In a different application, the same radio manufacturer originally designed in bent metal contacts for a battery application. While the radio was intended for consumer applications and hence it was assumed that reliability was not so critical. Unfortunately, the bent metal provided poor contact and battery life was undesirably short.
A manufacturer of spring contact probe-based connectors was able to integrate a very short spring contact probe within the design of the customer’s existing connector, to establish a positive ground (figure 52). Performance was increased to levels acceptable to the customer with little impact to their overall design.

Spring contact probes are often used in radios for frequently mated connections. An example would be the external microphone used with many radios (figure 53). Here, loose probes are populated into a printed circuit board in an array matching a set of pads on the side of the radio. The probe board is terminated to the microphone. By making the high-reliability probe-based microphone an option to a lower-quality microphone using bent metal contacts, the radio manufacturer
was able to offer a value-added product line for customers who were particularly concerned with reliability.

**Example 3: Right angle PCB interconnection in complex systems.**

Right angle interconnection of printed circuit boards frequently plagues designers of complex integrated systems for test and control applications in the electronic, military, aerospace and medical industries. Such applications often demand the frequent mating of one printed circuit board to another, as in a backplane or chassis based system, and pin-and-socket connectors often provide inadequate reliability and ease of use.

Applications often involve relatively high pin counts; and the mating force, alignment and long lockdown travel associated with pin-and-socket and bent metal edge card connectors cause stress to the assembly requiring cumbersome design considerations. Since pin-and-socket connectors feature withdrawal force, the mating mechanism must be designed to handle stress both in the compression and disconnection phases, increasing its complexity.

Connectors featuring spring contact probes can carry a relatively massive number of interconnections in a small space. They do not feature withdrawal force, and provide mechanical assistance during the disconnection operation. Spring contact probes offer much the same electrical performance as pin-and-socket connectors, even for RF and high current applications. Most importantly, they offer more consistent performance over multiple mating cycles, and an unbeatable record for service life.

The simplest form of right-angle connector involves a probe featuring a machined tail pin. Once the probes are installed in a block, this tail pin can be bent at a right angle to provide for through-hole interconnection with the main printed circuit board (figure 54). Any number of mounting
and alignment features can be built into the probe side of the connector, and heat stakes or screw holes can be provided on the solder side of the connector to take the mechanical load for the connector, rather than relying on the solder joints. The tail pin can also be bent completely around the block, allowing for surface mount interconnection to the basic board (figure 55).

This style of connector is adaptable to coaxial isolation of the spring contact probe for RF applications. It is even possible to use a probe that is double ended and bent at a right angle (figure 56), allowing for solderless interconnection on both sides.

Another approach involves the use of typical spring contact probes, again installed in a carrier block. The carrier block is slotted on its side to allow for the insertion of a strip of z-axis conductive elastomer. The side with the elastomer is compressed against the main board, establishing a solderless contact (figure 57). The compression force of the conductive elastomer, as well as its short cycle life, is non critical because of the limited number of cycles intended for this more permanent half of the interconnection. It is possible to use multiple rows of spring contact probes, each row employing
probes that are longer than the last, to allow for higher density with this form of interconnection (figure 58).

Very high-speed right angle interconnection of a resource card with a motherboard is a common application within the semiconductor test industry. Coaxial spring contact probes can be assembled into blocks that provide a common ground for shielding purposes (figure 59). Separate spring contact probes installed directly into the grounding block draw ground directly from the motherboard. The probes are terminated to coaxial cables, which can then be soldered or connected with pin-and-socket connectors to the driver cards. It is also possible to use coaxial spring contact probes that have individual concentric
shielding plungers (figure 60) to build similar connectors in isolating blocks. This allows for the preservation of discrete ground paths through the interconnection system.

Spring contact probes provide a unique means of solving right-angle interconnection challenges. Their low cost of development and the availability of many standard designs suits the low volumes and quick time-to-market of the systems in which they are called for. They add reliability and ease of both use and design to these systems, and allow them to provide the high degree of sophistication and value that are necessary in their target markets.

**Conclusion**

Thousands of connector applications have been improved by the use of spring contact probes. The scope of this work prevents us from providing examples of every type of application in which probes have been employed, but it is hoped that by describing these few utilizations we have illustrated some of the basic advantages of this type of connector.

In the cell phone applications discussed, spring contact probes represent a revolution in a field normally dominated by pin-and-socket based RF connectors. By employing
probes, the customer is able to greatly reduce the cost of both the connector and the labor required to assemble it. More importantly, the reliability of that connection was vastly improved, resulting in less field returns. In streamlining assembly processes and improving product quality, the probes saved the cell phone manufacturer many times the difference in component costs alone.

The most conventional advantage of a spring contact probe based connector, their remarkable reliability over thousands of mating cycles, is illustrated in the case of military handheld radios. However, there are scores of other frequent-mate applications which have been improved in this regard through the employment of spring contact probes. They are used for data and battery interconnection in global positioning systems, personal digital assistants, cellular phones, portable medical equipment, and the products of many other industries. No other connector type offers the field survivability of spring contact probes, and engineers discover this on a daily basis.

Complex system interconnection is one of the most challenging and successful applications for spring contact probe based connectors. Designers of such systems need solutions which perform at the very highest levels of performance. The connectors used inside such systems must not occasion frequent service calls; they must offer high reliability and user serviceability. Such connectors incorporate several customized materials; coaxial cables and spring contact probes, flexible and rigid printed circuits, and complex mechanical docking features are all frequently in use. The connector designer must have the experience and innovation necessary to incorporate all of these elements in a manner which is cost-effective and of the highest quality, in a time frame which does not affect the time to market of the final product. Here, the custom engineering skills of the probe-based connector manufacturer is of the highest value.
Spring contact probes can improve the performance, cost, and reliability of applications ranging from a ten dollar remote control to a billion dollar semiconductor test system. Connector manufacturers who are adept at their advantages can offer the end user an incredible design partner, providing turnkey solutions which can truly revolutionize the final product. These few examples serve to demonstrate some ways in which this has been done, but there are many other possible products which stand ready to be improved by spring contact probes — and one of them could be that which the reader of this book is designing.
Appendix 1
Basic Spring Contact Terminology

All spring loaded contact probes are very similar in their basic structure. They are primarily comprised of 3 parts: the plunger, barrel and spring. Double-Ended Probes generally have two plungers, a barrel and a spring. One variation is a bias ball design that includes a plunger, a ball, a barrel and a spring.

Basic Assembly

During assembly, the spring is placed inside the barrel. Then, the plunger is inserted into the barrel. (In the case of bias ball designs, the ball is placed inside the barrel after the spring, then the plunger). The plunger is compressed, setting the spring in a state called pre-load. To hold the plunger in pre-load position, a crimp is placed on the barrel. The crimp can be one of several variations. A standard spin or dimple crimp can be placed on the body of the barrel. Or, the top of the barrel can have a roll over crimp (commonly used in short probes where a long travel is needed).
And in some cases, the connector housing is designed to keep the probe in its pre-load state.

Spring contact probes can also be used within a mating receptacle. The receptacle houses the barrel portion of the probe, leaving the plunger extended. This design makes it easier to field refurbish the probe. When a probe has reached its maximum life, it can be easily pulled from the receptacle and replaced with a new probe.

**Coaxial Probes**

Coaxial probes have the signal conductor of a standard probe. The difference between these probes and others is that an insulator, usually air or Teflon, housed by a ground shield, surrounds the signal probe. Coaxial probes are also available with a spring loaded shielding plunger. This allows the ground to be carried directly to the PCB or device under test.

**General Probe Definitions**

When discussing probes, especially when ascertaining specifications for the most suitable probe, several topics are consistently referenced:

- **Recommended Minimum Centers** — The minimum distance from the centerline of one mounting hole to the next. Or how close the probes can be placed next to each other.
- **Maximum Travel** — The maximum distance the probe can compress. Also referred to as the maximum compliance or stroke.
- **Rated Travel or Working Travel** — Typically 2/3 of the maximum travel. This is the recommended distance the probe should be deflected during use. Variations in target
positions and geometries can cause the probe to under or over stroke. By setting the application to nominally use 2/3 the maximum travel, there is ample travel remaining in the probe to absorb these variations without damaging the probe or unit under test.

• **Current Rating** — The maximum current a probe can carry for one hour. Determined by the power (heat) generated by the current and resistance (I²R) and the ability of the probe and housing to dissipate this heat. Current ratings are specified at ambient temperatures.

• **Contact Resistance** — The typical resistance of the probe over its life. Dependent upon the base materials, platings, physical bulk and design.

• **Pointing Accuracy** — The radial area that the probe tip will hit over multiple cycles. Determined by the probe design.

**High Frequency Definitions**

High frequency applications (coaxial probes and short probes) have an additional set of specifications:

• **Impedance** — The characteristic property of a transmission line describing the ratio between electric and magnetic fields.

• **Bandwidth** — The maximum frequency at which the probe can carry the signal at no more than 1 dB loss.

• **Self-Inductance** — The property of a probe that opposes a change in current flow, thus causing current changes to lag behind voltage changes.

• **Capacitance** — The measure of the coupling between the signal conductor probe and the ground shield.

• **Insertion Loss** — The loss in load power due to the probe. Ratio of the power received at the load before the probe to the power received at the load after the probe.
Interface or Connector Housing Definitions

When the probe is assembled into units, other factors come into play.

- **Keeper Plates** — In blocks and interfaces, keeper plates are used to hold probes in their housing.

- **Common Ground** — In common ground blocks, the probes are directly installed in a gold-plated conductive ground block.

- **Isolated Grounds** — If all grounds are to be isolated, a non-conductive block is used.

- **Isolated and Common Grounds** — For a mixture of common and isolated grounds, the common ground probes are installed directly in the conductive block, while the isolated ground probes are installed with an insulator placed between the probe and common ground block.

- **Signal and Power Probes** — In isolated ground blocks, signal and power probes are installed directly into the non-conductive block. In common ground blocks, the signal and power probes are isolated from the ground block by an insulator. Controlled impedance designs are available in either isolated, common or mixed ground configurations.
Appendix 2
Spring Contact Probe Tip Styles

The ability to make a good, repeatable electrical contact is extremely important. That is why the choice of tip style is extremely important. The application and target determine the tip style.

For Testing Pads

Gold-plated pads — These are generally tested with a spherical radius tip or a flat tip. When testing gold pads, contamination and oxidation are not an issue. Using a less aggressive tip style minimizes, if not eliminates, any damage or witness marks to the pad.

Solder pads — Contaminants and oxides are generally present on the surface of these pads so the tip must be sharp and aggressive enough to penetrate. Typically the tips used for this application are spear points, chiseled spears, chisels or 4-point crowns.

Bare copper pads — Similar to solder pads, except the contaminants are more difficult to penetrate. Therefore, a spear point or chisel spear is the best option.

For Through Holes or Vias

The preferred tip choices for testing through holes or vias are the chiseled spear points or chisels. Only the edges of these tips contact the perimeter of the via or through hole.

For Test Sockets

For contacting area array packages in test sockets, a 4-point crown tip is recommended. This allows the ball or lead to center within the plunger tip, preventing damage to the center area where soldering must occur. The 4-point crown also allows the ball to self-center within the tip. Single points are not considered a good option for this application in that they can slide off the ball and miss the
target altogether. Cup tip styles may be used for this application, but contaminants have a tendency to accumulate in the tip and can then block current transfer. Routine cleaning and preventative maintenance have proved to eliminate these contact issues.

**For Interfaces**

Chisel, chisel spears, or spherical radius tips are commonly used depending upon the type of contact which must be made.

**For Terminals**

For contacting terminals inside a connector — cup, serrated or 4-point crown tips are recommended. These tips will allow the terminal to self-center within the tip. As with the test sockets, cup tips have a tendency to accumulate contaminants in the tip and can then block current transfer.

**Plunger Tips and Usage**

**Concave Tips — A or G**

Concave tips are used in applications where the object to be contacted will protrude from their surroundings. The cup shape helps guide longer or slightly misaligned contact points towards the axis of the probe, helping to ensure that contact is linear. Since the probe has a working clearance, the tip will shift slightly to conform to the location of the point to be contacted. Concave tips are annular, having no sharp edges that mate with the contact point; for this reason, they are a poor choice for contact points that may be oxidized or would otherwise require aggressive contact. Concave tips also have a tendency to fill with dirt, and may require some maintenance. This is particularly true if the normal orientation of the tip is up, as gravity will not assist the process of debris clearing the cup surface.
Spherical Radius Tips — D or J

One of the more common tip styles chosen for connector applications is the spherical radius. A round tip tends to make minimal indentations and witness marks into its mating contact point, and is often the best choice for repeated contact. Also, rounded tips are often chosen when the contact point is likely to slide across the probe tips during the mating cycle. Rounded tips are annular, having no sharp edges that mate with the contact point; for this reason, they are a poor choice for contact points that may be oxidized or would otherwise require aggressive contact. Contact between the radius and the contact point may be blocked by relatively small contaminants, since the rounded tip has no point or edge to pierce or wipe through obstacles.

Flat Tips — C or F

Flat tips are sometimes chosen to mate with relatively large pads. The typical intent of this selection is to maximize the contact area between the probe tip and the contact pad. However, it should be noted that flat tips rarely strike their targets in a perfectly perpendicular fashion, and as such the actual contact footprint often takes on a crescent shape. Further, the annular nature of flat tips means that they have no means of penetrating oxides or other obstacles, and it is quite possible for them to be blocked from contacting their intended target by relatively small particles of debris. Flat tips are also occasionally selected for contact with slightly protruding targets that are not likely to be axial with the contact probe, as their diameter allows contact despite some misalignment.
Serrated Tips — H or HT

In the proper environment, serrated tips often produce the best electrical contact of all tip styles. They have many parallel points of contact, which allows current to flow through several redundant paths; even when the probe strike is not perpendicular, they normally can be counted on to make contact with at least three points. They are not so aggressive that they leave large indentations, and the fact that the probe’s spring force is spread among so many points of contact often means that they leave the least significant witness marks of all tip styles. They can be used to contact flat or protruding targets with equanimity. Their polygonal shape makes them slightly more expensive to produce than the annular tips discussed up to this point. Like flat tips, large serrated tips are sometimes used to make up for misalignment inherent in the application. The serrated tips can also be tapered to ensure contact with smaller targets.

Conical Tips — E or B9

Conical tips are used to contact metallized female targets. These may be evidenced as connector receptacles, plated through holes in a printed circuit board, or concave PCB vias partially filled with solder. In these applications, the conical tip will center in the female receptacle or plated through hole, allowing positive alignment. However, the contact surface will be annular, and contact will easily be blocked. For this reason, conical tips would normally only be selected where it was critical to not mar the edges of the receptacle or plated through hole. Conical tips are, however, often a very good choice for small pads or other flat contact points. They deliver all of their spring force into a relatively small contact area when mating with a pad, and penetrate contaminants effectively. They
will generally produce fairly significant indentations, and should be carefully evaluated before being used in a repeated contact application.

**Chisel Tips — S, SW or T**

Chisel tips are very similar in form and application to conical tips. Chisel tips are effectively conical tips that have had three or more flat planes added, which descend from the tip. This provides knife-like edges that cut into the surface of the plated through hole or receptacle, ensuring contact despite heavy oxidation. Chisel tips are a common choice for plated through holes of most types, as well as pads which feature an unfilled via.

**4-Point Crown Tips — W, U or UST**

Multipoint crown tips are used in a broad number of applications, roughly matching those of the serrated tip. Where serrated tips have their points cut in a regular fashion, however, the points on a crown tip are deeply relieved. A “self-cleaning” valley is cut between each pair of points, which allows contaminants to easily fall free. Thus, regular and tapered four point crowns can be used with more reliability in contaminated environments than their serrated parallels. The knife-like edges on the inside of the crown also help make contact with convex and protruding contact points, wiping across their surface and cutting through contaminants. Crown tips typically provide the most secure electrical contact, particularly where contamination is a possibility. While they spread their spring force among multiple points, and therefore do not have the penetrative capabilities of single conical tips, they are fairly aggressive. Since they are polygonal and relatively complex in shape, they tend to be the most expensive tip configuration.
Multi-Point Tips — TX or X

Many attempts have been made to combine the virtues of the chisel’s contact to female targets and the multi-point crown’s effectiveness on pads and convex contact points. The best of these involve cutting points on a relatively small diameter into the tip of a chisel, either by using two intersecting cuts in to produce self-cleaning valleys or using a simple slotting cut to produce a more defined point. These tip styles are relatively universal, and are an excellent choice when the contact configuration is variable. Since the tips are on a small diameter, these tips will not compensate for misalignment to the degree that a pure chisel would; and since the diameter of the points is relatively restricted, they are slightly less forgiving than a more open multipoint crown would be. However, for some applications they represent a valid compromise. Like other multipoint crown tips, they are relatively expensive.
Appendix 3
Pointing Accuracy as Related to Probe Construction

Pointing accuracy is defined as the radial target area in which a probe is expected to contact. The primary factors affecting pointing accuracy are determined by the probe design. The extended length of the plunger from the barrel, the retained length of the plunger in the barrel, and the working clearance between the plunger and the barrel are the three primary factors that determine pointing accuracy.

Other factors that determine pointing accuracy are the straightness of the drilled hole and the clearance between the drilled hole and the probe. These factors will not affect the radial area where the probe can be expected to hit, however, these factors will shift the center point of this area.

![Diagram showing pointing accuracy and shift](image-url)

Dark circle is the radial pointing accuracy of .002". Lighter circle represents the shift in pointing accuracy. This represents the target area that the probe will hit.
Formula For Calculating Pointing Accuracy

Pointing accuracy for most spring contact probes is calculated with the following formula (figure 66):

\[ e = \frac{1}{2}c \left( \frac{a}{b} + 0.5 \right) \]

where

- \( e \) = pointing accuracy
- \( a \) = extended length of the plunger
- \( b \) = retained length of the plunger
- \( c \) = working clearance between the plunger OD and barrel ID

Now let’s apply this formula in some examples. Each of these probes is designed with a roll top crimp. This type of crimp is utilized because the travel is relatively long as compared to the overall length of the probe (figure 67).

A typical socket probe has an overall length of .225”, maximum travel of .0255” on each end, and mounting centers of .039”. In this design,

- \( c = .001 \)
- \( a = .0395 \)
- \( b = .020 \)

The pointing accuracy =

\[ \frac{1}{2}(0.001)(0.0395/0.020 + 0.5) \]
\[ = 0.0005(1.975 + 0.5) \]
\[ = 0.0005(2.475) \]
\[ = 0.0012” \]

A battery contact probe has an overall length of .395”, maximum travel of .090”, and mounting centers of .200”. In this design,

- \( c = .002 \)
- \( a = .115 \)
- \( b = .060 \)
The pointing accuracy
\[ = \frac{1}{2}(0.002)(0.115/0.060 + 0.5) \]
\[ = 0.001(1.917 + 0.5) \]
\[ = 0.001(2.417) \]
\[ = 0.0024" \]

**Ways to Improve Pointing Accuracy**

There are two basic ways to improve pointing accuracy in a probe design:

- **Reducing the working clearance** — This is the most difficult method of improving pointing accuracy. In order to absorb manufacturing tolerances, anything less than 0.001” of working clearance is not feasible.

- **Decrease the ratio between the extended length of the plunger and the retained length of the plunger** — A better option to enhance pointing accuracy. However, when length or travel constraints exist, this method becomes increasingly difficult.

![Chart showing actual pointing accuracy of three probe designs](image-url)

*Fig. 68*

This chart shows the actual pointing accuracy of three probe designs for a 100 mil center, .250 travel probe.
Increasing the retained length of the plunger will have the identical effect on the overall length of the probe. For every .001” increase in the retained length of the plunger, the overall length must increase by .001”. Reducing the extended length of the plunger could affect the maximum travel of the plunger if the maximum travel and the extended length of the plunger are identical. If not, the extended length can be reduced to equal the maximum travel of the probe.

The length of the barrel is determined by the maximum travel and retained length of the plunger. As a general rule, the pre-load length of the spring must be twice the maximum travel. For instance, if a probe has a maximum travel of .050”, the pre-load length of the spring would need to be .100”. So the barrel must house the pre-load length of the spring and the retained length of the plunger. In a bias ball design, the size of the ball must be added to the barrel length.

When the overall length of the probe is not a limiting factor, other probe constructions become more feasible. In the PCB test industry, a large majority of probes feature a crimp located approximately 1/3 down from the top of the barrel.

**When Pointing Accuracy is Critical**

When pointing accuracy is of critical importance, a bifurcated probe is most reliable. The barrel is precision machined to form four contact beams at the top, where the plunger exits the barrel. These four beams are then coined to perfect center, in an interference fit with the plunger. This bifurcated configuration completely eliminates all working clearance and the problems associated with plungers being intentionally forced off-center as with bias ball, bias plunger and bias spring probe designs.
Appendix 4
Materials and Platings

The application and the ability of the material to be machined determine the base materials used for a probe. Resistance is a primary concern when designing a probe and selecting materials and platings. As probes become smaller and less dense, their current carrying capacity decreases and their resistance increases. The material selected for the probe plays a key factor in maintaining or enhancing current carrying capacity and the resistance of the probe.

Barrel Materials

The great majority of barrels are made from nickel silver. Nickel silver is used because of its high strength, ductility and ability to be machined or deep-drawn. Barrels that require a step flange for mounting in a printed circuit board must be machined. Barrels that are in essence a tiny tube, are usually deep-drawn. Alternative materials for machined barrels are beryllium copper or brass. For deep-drawn barrels, alternative materials include phosphor bronze or brass.

Nickel silver is an alloy of copper, nickel and zinc with excellent resistance to corrosion and does not oxidize or tarnish readily in ambient environments. As such, nickel silver barrels do not require plating. However, most nickel silver barrels are gold plated, to lower resistance and to ensure electrical performance (figure 71). Gold plated

<table>
<thead>
<tr>
<th>Spring Materials</th>
<th>Nickel/Silver</th>
<th>Gold Plated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistivity (Ω cir mil ft)</td>
<td>186.5</td>
<td>11.4-28.9</td>
</tr>
<tr>
<td>Hardness (Rockwell B)</td>
<td>40-55</td>
<td>78-86</td>
</tr>
<tr>
<td>Tensile Strength (ksi)</td>
<td>65</td>
<td>16-31</td>
</tr>
<tr>
<td>Yield Strength</td>
<td>25-27</td>
<td>—</td>
</tr>
</tbody>
</table>

Fig. 71
barrels can be used in almost any environmental extreme. And a probe with a gold plated barrel performs better.

**Plunger Materials**

The base material is one of the most important factors determining the performance of a probe (figure 72). Conductivity, strength and wear characteristics are the major criteria considered for plunger base material. Plungers are almost always made of beryllium copper. Tool steel and stainless steel plungers are other options, but as diameters decrease, steel becomes harder to machine. Steel is also more expensive, but it is harder and has a longer tip and edge life. It also has higher resistance and is magnetic.

**Plunger Base Materials**

<table>
<thead>
<tr>
<th></th>
<th>BeCu</th>
<th>Tool Steel</th>
<th>Stainless Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistivity (Ω cir mil ft @ 20°C)</td>
<td>34.7</td>
<td>120.3</td>
<td>342.9</td>
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<tr>
<td>Hardness (Rockwell C scale)</td>
<td>36-52</td>
<td>50-55</td>
<td>48-50</td>
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<tr>
<td>Hardness (Knoop)</td>
<td>361-425</td>
<td>542-629</td>
<td>512-542</td>
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<tr>
<td>Tensile Strength (ksi) (Heat Treated)</td>
<td>200</td>
<td>216</td>
<td>230</td>
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<tr>
<td>Yield Strength (ksi) (Heat Treated)</td>
<td>182</td>
<td>152</td>
<td>195</td>
</tr>
<tr>
<td>Modulus of Elasticity in Tension (Mpsi)</td>
<td>19</td>
<td>30</td>
<td>29</td>
</tr>
</tbody>
</table>

Fig. 72

**Spring Materials**

Springs are manufactured from beryllium copper, stainless steel or music wire. Each of the three materials has unique characteristics. There are three primary considerations in choosing a spring material: operating temperature, resistivity and the required force (figures 74 and 75).

- **Beryllium copper** can operate at up to 205°C for 1 hour and has a low resistivity and strength. Higher spring forces cannot be manufactured from beryllium copper.
- **Music wire** is used for extremely high force springs as it has a reasonable resistance, but cannot operate at temperatures above 120°C.
**Stainless steel** has the highest operating temperature at 260°C for 1 hour, the highest resistance, and a strength between that of the other two materials.

### The Plating Process

Most probe components are plated using a barrel plating process. Parts are placed inside a container, which in turn is placed in the plating bath. The container then rotates to make sure all parts are completely exposed to the plating bath. There are two types of plating processes used: electroless and electroplating.

Electroless plating involves a chemical reduction reaction where the reduced metal is the catalyst for the reaction. No current is required for deposition of electroless nickel. The electroless bath provides a deposit that follows all contours of the substrate exactly, without building up at the edges and corners. A sharp edge receives the same thickness of deposit as does an internal diameter. Almost all parts are electroless nickel plated as a base coat. The thickness of the deposit varies with the component.
Electroplating is a process by which metal in ionic form migrates from a positive to a negative electrode. An electrical current passing through the solution causes objects at the cathode to be coated by the metal in solution. Electroplating is done to protect and increase the corrosion resistance, conductivity, or solderability.

Rack plating is used for large parts such as common ground blocks. Parts are strung onto the cathode and are then submerged into a plating bath.

The Plating of Components

In plating probe barrels, it is extremely important to have an opening on each end of the barrel to allow a free flow of the plating bath solution through the barrel. Since there is a limited amount of gold ions in the solution, the solution must be able to move freely inside the barrel. Once the parts have been plated, it is important that they are thoroughly cleaned and rinsed to remove residues from the plating bath. Fluid transfer is critical to successfully complete this process.

An alternative plating process is necessary when the barrel being plated is closed at one end. It is a difficult and costly plating process but it is one of the only ways to ensure plating material is deposited on the inside of the barrel.

Plungers are plated to ensure:
- The base material is protected from oxidation or corrosion
- There is a clean, nonoxidized, conductive surface at the juncture between plunger and barrel, which is critical to the current path
- The overall resistance of the component is lowered by providing a less resistive current path in parallel
- The base material is protected from wear and/or abrasion

Gold is the preferred plating, because it provides excellent conductivity and high resistance to corrosion. Nickel, commonly used throughout the electronics industry, is used
as a barrier plating between the base metal and the precious metal plating to prevent migration of the base material into the precious metal. Duralloy, a proprietary plating, is exceptionally resistant to corrosion and oxidation. Duralloy is slightly more resistive than gold, and is therefore not recommended for extremely sensitive measurements.

Springs are plated using either silver or gold. Silver has a high thermal and electrical conductivity. The intrinsic properties of gold prevent oxidation and corrosion.

The properties of electro or electroless deposited metals (figure 70) vary from that of the wrought metal. The primary reason for the variation is due to the grain size of the metal as plated or wrought. Deposited metals generally feature a smaller grain size than the wrought metal. For this reason, the hardness and tensile strength of deposited metals is considerably higher than that of their wrought equivalent. Impurities and alloying elements inherent in the production of deposited metals account for their higher resistivity (figure 73).

<table>
<thead>
<tr>
<th>Properties of Gold</th>
<th>Plated</th>
<th>Wrought</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistivity (Ω cir mil ft)</td>
<td>11.4-28.9</td>
<td>14.7</td>
</tr>
<tr>
<td>Hardness (Knoop)</td>
<td>160-190</td>
<td>80</td>
</tr>
<tr>
<td>Hardness (Rockwell B)</td>
<td>78-86</td>
<td>35</td>
</tr>
<tr>
<td>(Rockwell C)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Tensile Strength (ksi)</td>
<td>16-31</td>
<td>14.9</td>
</tr>
</tbody>
</table>

Fig. 70

<table>
<thead>
<tr>
<th>Plunger Platings</th>
<th>Gold</th>
<th>Nickel</th>
<th>Duralloy™</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistivity (Ω cir mil ft)</td>
<td>11.4-28.9</td>
<td>181.5-331.0</td>
<td>64-90</td>
</tr>
<tr>
<td>Hardness (Knoop)</td>
<td>160-190</td>
<td>500-600</td>
<td>930-1100</td>
</tr>
<tr>
<td>Hardness (Rockwell B)</td>
<td>78-86</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>(Rockwell C)</td>
<td>–</td>
<td>47-53</td>
<td>&gt;68</td>
</tr>
<tr>
<td>Tensile Strength (ksi)</td>
<td>16-31</td>
<td>100-122</td>
<td>101-112</td>
</tr>
</tbody>
</table>

Fig. 73
Properties of Metals

Resistivity

Resistivity is the resistance to current flow. The unit of resistivity, $\Omega \text{ cir mil/ft}$, refers to a sample one foot in length with a cross section area equivalent to that of a circle with a diameter of .001”.

Hardness

Hardness is the resistance of a material to a local penetration, scratching, machining, wear or abrasion, and yielding.

Tensile Strength

Tensile strength is the maximum stress in tension that a material can withstand before rupture. Calculated by dividing the maximum load by the original cross sectional area.

Yield Strength

Yield strength is the stress at which a material exhibits a specified amount of permanent deformation. In tensile testing, 0.2% offset on the stress-strain curve is generally used.

Modulus of Elasticity

Modulus of elasticity is the ratio of stress to strain within the elastic range of a material. This is a measure of the material’s ability to resist deflection when a load is applied.

Modulus of Torsion

Modulus of torsion is the ratio of stress to strain when the stress is applied in a twisting motion.

Operating Temperature

The maximum temperature a probe can withstand without permanent damage to the probe. It should be noted that at extreme operating temperatures mechanical life may be reduced. Prolonged exposure time significantly reduces the maximum operating temperature.
Appendix 5
Electrical Performance and Resistance

Kelvin Life Cycle Test

The 4-Wire Kelvin Life Cycle Test is an important step in the design evaluation process. Synergetix has developed a new generation of programmable Life Cycle Test Systems capable of delivering fast and accurate feedback to our design engineers. Each test system is capable of determining the reliability and performance characteristics of our probes. This ensures that the electrical and mechanical performance of each probe meets engineering specifications, as well as customers' expectations. Each system was designed with an open architecture, allowing for the flexibility necessary to adapt to the growing needs of the ATE industry.

Typical Test Set-up

1. Up to 64 spring contact probes are installed into receptacles that have been press fitted into a matrix of holes drilled into a G-10 fiberglass block.
2. The G-10 block is mounted firmly to a stage with the contact probes perpendicular to the test platen. The platen used is made of copper, plated with .005 inches of silver, and 50 micro-inches of gold to contact the probe tips.
3. The test platen is mounted to a precision cross roller slide driven by a cam and micro-stepper motor. At set-up, the mechanical stroke of the probe can be controlled with great precision.
4. Test cables are soldered to each receptacle and plugged into multiplexers that route the signals to the digital multi-meter and current source.
5. The program, written with LabVIEW™ Version 5.1,
controls all aspects of the test such as current settings, stepper motor speeds, mechanical stops for resistance, stroke loss and pauses.

6. The software also features on-screen SPC analysis, which is available at any point during the test.

**Physical Parameters**

1. Resistance is measured using the 4-wire Kelvin test. This method uses a pair of wires to supply constant current to the device under test (DUT). A separate pair of wires measures the voltage drop across the DUT. This method allows the system to void the resistance of the measuring leads. The resistance of the test platen is then offset with software. The system is calibrated at regular intervals with standards traceable to the National Institute of Standards Technology. The system has proven accuracy to within +/-.5 milliohms. The 5 ½ digit multimeter is directly connected to the PCI slot of the computer and acts as the data acquisition card as well. This allows information to be digitized and transferred directly across the 100 MHz bus of the computer without cables.

2. The current source provides constant current to the DUT. The output current is verified before the DMM triggers the multiplexer and is corrected programmatically if needed. This provides repeatable measurements over time and eliminates current drift. The current is adjustable from .010 to 1 amps with a maximum compliance voltage of 125 volts DC.

3. The cycle rate is set at 4 Hertz for most tests, but can be adjusted from 1 to 12 Hertz programmatically.

4. The LabVIEW™ software used to program the test system gives the flexibility needed to meet the changing demands of the ATE industry. The open architecture allows changes to be made quickly to adapt to our customers’ needs.
Operating Temperature and Resistance

An environmental chamber has been incorporated into our life cycle testing capabilities. This gives us the ability to test our probes at temperatures ranging from -60° to 160° Celsius. Temperature effects on probe resistance can be accurately measured to provide our design engineers and customers with temperature data as required (figure 76).

Coaxial and RF Principles

The impedance of a coaxial line can be determined by the ratio of the diameters and the dielectric constant (figure 77).

D=Diameter

d=Inside Diameter

$\varepsilon_{\gamma}$=Dielectric Constant

Cable Inductance, L, is determined by the ratio $D/d$

Cable Capacitance, C, is determined by the $D/d$ and the dielectric constant $\varepsilon_{\gamma}$ of the insulator
The impedance of a coaxial line is determined by the ratio \( D/d \) and by the dielectric constant \( \varepsilon_\gamma \) of the insulator (figure 78).

A reduction either in signal conductor diameter or dielectric constant increases impedance (figure 79).

Air is the constant which all dielectric constants are measured against. Every other insulative material has a higher dielectric constant which reduces the velocity of propagation, and therefore reduces wavelength (figure 80).

<table>
<thead>
<tr>
<th>Impedance</th>
<th>Air ( \varepsilon_\gamma = 1 ) PTFE</th>
<th>( \varepsilon_\gamma = 2.05 )</th>
<th>PE ( \varepsilon_\gamma = 2.28 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>50Ω</td>
<td>2.30</td>
<td>3.30</td>
<td>3.52</td>
</tr>
<tr>
<td>75Ω</td>
<td>3.49</td>
<td>6.00</td>
<td>6.60</td>
</tr>
</tbody>
</table>

Fig. 78

Discontinuity as a Result of Lower Impedance (Smaller Insulator Diameter)
• When a traveling wave reaches a discontinuity such as a change in diameters or a change in dielectric constants, a fraction of the wave will be reflected.
Appendix 6
Independent Lab Test Results

CHIP SCALE PROBE 0.5MM PITCH SOCKET

Objective
The Synergetix 0.5mm BGA socket was measured at GigaTest Labs to assess its electrical performance. A SPICE-compatible lumped element model was derived from the measured data. Also, its high-speed performance limits were determined.

Methodology
The BGA socket was mounted onto a custom PCB, designed to exhibit low parasitics and allow the use of coplanar probes. A second PCB with measurement standard patterns was mounted inside the socket. This would allow pins to be measured under three conditions (open, shorted and thru). The HP MDS (Microwave Design System) software was then used to extract an equivalent-circuit model which is SPICE compatible.

Measurement System
All measurements were taken using a high-frequency measurement system. This consists of a Hewlett-Packard 8510C network analyzer & GGB Picoprobes™ 450 micron pitch. The HP 8510C network analyzer is a frequency domain instrument. The measurements are taken as scattering parameters (a.k.a. s-parameters). The HP 8510C has great calibration capabilities, which make it the most accurate high-frequency instrument available. For this work the short-open-load-thru (SOLT) calibration was used. The GGB Picoprobes provide a high-quality 50 Ohm path from the network analyzer and cables to the DUT.
Equivalent-Circuit Model

Figure 81 shows the topology used to model the BGA socket.

Element Definitions
(Figure 82)

- **L1, L2**: pin self-inductance
- **M21**: mutual-inductance between adjacent pins
- **R1, R2**: shunt-resistance of inductors L1 and L2 used to model high-frequency loss due to skin effect and dielectric loss
- **C21a**: mutual-capacitance between adjacent pins (PCB side)
- **C21b**: mutual-capacitance between adjacent pins (BGA side)

<table>
<thead>
<tr>
<th>pins</th>
<th>L1 &amp; L2 (nH)</th>
<th>M21 (nH)</th>
<th>R1 &amp; R2 (Ω)</th>
<th>C21a (pF)</th>
<th>C21b (pF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>field adjacent</td>
<td>0.50</td>
<td>0.06</td>
<td>80</td>
<td>0.040</td>
<td>0.050</td>
</tr>
<tr>
<td>field diagonal</td>
<td>0.50</td>
<td>0.01</td>
<td>90</td>
<td>0.007</td>
<td>0.008</td>
</tr>
<tr>
<td>edge adjacent</td>
<td>0.55</td>
<td>0.07</td>
<td>100</td>
<td>0.045</td>
<td>0.045</td>
</tr>
<tr>
<td>corner adjacent</td>
<td>0.67</td>
<td>0.08</td>
<td>115</td>
<td>0.050</td>
<td>0.050</td>
</tr>
</tbody>
</table>

Element Values

The BGA socket model is valid from DC to 3.05 GHz. The measured and modeled transmission response agrees within 0.1 dB. A model was extracted for four types of pins: adjacent field pins, field pins oriented diagonally, edge pins and corner pins.
The bandwidth of the socket was determined from a loop-thru measurement on two adjacent pins. The nearest row of pins was grounded (figure 83). The 1 dB bandwidth is 6.4 GHz, (figure 84). The model bandwidth is DC-3.05 GHz, which will easily handle signals with 300 ps edges.
Synergetix BGA Socket (0.5mm Pitch)
Open Measurement on Adjacent Pins

Reflection response – meas (triangle) vs sim (square)

Crosstalk between adjacent pins – meas (solid) vs sim (square)

Reflection response – meas (triangle) vs sim (square)

Figure 85a
Electrical Performance
Synergetix BGA Socket (0.5mm Pitch)
Shorted Measurement on Adjacent Pins

Reflection response – meas (triangle) vs sim (square)

Crosstalk between adjacent pins – meas (solid) vs sim (square)

Reflection response – meas (triangle) vs sim (square)
Synergetix BGA Socket (0.5mm Pitch)
Thru Measurement on Adjacent Pins

Reflection response – meas (solid) vs sim (square)

Crosstalk between adjacent pins – meas (solid) vs sim (square)

Reflection response – meas (triangle) vs sim (square)

Figure 85c
Electrical Performance