EVOLUTION OF BRAID AND OVERBRAID MATERIALS FOR AEROSPACE SHIELDING APPLICATIONS

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INTRODUCTION

The aerospace industry has been using metal braids in cables and overbraids on electrical harness assemblies for decades. The introduction of plated fibers in the 1990's altered the landscape as designers weighed the performance of heavy copper braids versus lighter weight alternatives to meet EMI/EMC requirements. This paper will discuss the evolution and history of metalized and other braids, their current state, and performance strengths and weaknesses. It will also offer equivalent strategies using advanced copper alloys to improve performance while offering size and weight reduction opportunities.

HARNESS METAL OVERBRAIDS

Aircraft designers have used the requirements for braid strand selection listed in NEMA WC27500 "**Standard for Aerospace and Industrial Electrical Cable**" Table 3-5 (formerly MIL-C-27500) to determine the strand size based on harness diameter for metal braids and overbraids used on electrical harness assemblies (See Table 1). The values listed in the table were developed in the 1950's and 1960's timeframe and utilized material readily available and accepted by the aerospace community at that time which were all plated soft copper.

Table 1: NEMA WC27500 Table 3-5

Group A Cable Core Diameter	Group B Cable Core Diameter	Shield Strand Size
0.000 to 0.060 inch	0.000 to 0.250 inch	38 AWG
0.061 to 0.310 inch	0.251 to 0.400 inch	36 AWG
0.311 to 0.750 inch	0.401 to 1.00 inch	34 AWG
0.751 inches and larger	1.001 inches and larger	32 AWG

Sizing criteria was based on meeting the basic shielding effectiveness and optical coverage requirements while having enough metal mass to withstand the forces associated with handling, routing and the final installed configuration of typical electrical assemblies with a minimum 6X bend radius. They also took into account conditions where cyclic flexing was required such as landing gear or wing folds with a minimum service life of 20 years. Thus, the break strength of the copper braid strands was a primary characteristic in determining size selection.

The majority of products used today in aerospace are defined as Group B configurations. These products are made from insulating materials with excellent elongation and flexibility characteristics and also tend to have significantly thinner insulation walls for both the primary wire insulation and the jacket insulation. Products defined in Group A tend to be mechanically stiffer and have very thick insulation walls.

Aircraft designers generally referenced either QQ-B-575 **"Braid, Wire (Copper, Tin Coated, or Silver Coated, Tubular or Flat)"** or A-A-59569 **"Braid, Wire (Copper, Tin Coated, Silver Coated, or Nickel Coated, Tubular or Flat)"** in their process specifications which provides braiding equipment setup characteristics and unique part numbers for coated soft copper slide-on tubular braid. A-A-59569 does not cover copper alloy or stainless steel configurations. Based on the design characteristics noted in "Table I. Braid Dimensions and Data" within A-A-59569, the diameter range which is used for each strand size can be extracted and is given in Table 2 below. It should be noted that A-A-59569 allows a much wider diameter range for each shield strand size when compared to WC27500.

Most aircraft manufacturers have adopted WC27500 group B requirements and included them in their respective process specifications for harness metal overbraiding. 38 gauge is not commonly used in order to reduce the number of braid machine changeovers required during the braiding process. Another consideration that aircraft designers must include in determining the proper strand size selection is lightning strike protection for both critical circuits and the attached avionics equipment. This is where braid conductivity, transfer impedance, and low frequency performance play a much more significant role in controlling transient and power dissipation to aircraft ground.

Table 2: Harness size range permitted for each strand size as per A-A-59569

Minimum Cable Core Diameter	Maximum Cable Core Diameter	Shield Strand Size
0.031”	0.781”	36 AWG
0.062”	0.781”	34 AWG
0.062”	0.781”	32 AWG
0.375”	2.000”	30 AWG

Over the years, WC27500 has added additional shielding materials including copper alloys, flat stands of various alloys, stainless steel, and nickel-chromium alloy without adjusting Table 3-5 to account for the change in tensile break strength and resistance associated with the new material classes. The lone exception is round stainless steel where 40 gauge is used for diameters up to 0.060 inches, 38 gauge on diameters from 0.060 to 0.120 inches and 36 gauge in applications above 0.120 inches. The tensile rating and conductivity of the various classes of materials used in metal harness overbraid applications will be discussed later in the paper.

In the late 1990's, new classes of materials entered the market to reduce the weight and volume profiles of metal harness overbraids. These materials will be explored in depth but are summarized in SAE AIR5456A "**Metal Clad Fibers for Electrical Shielding & Harness Overbraid**". At the same time, producers of aerospace copper alloys (such as Fisk Alloy) were developing replacements for High Strength Cadmium/Chromium Copper Alloy (Alloy 135) to address hazardous metal and RoHS compliance concerns.

The increased concern of conductor performance and conductor integrity led the SAE AE-8D committee adopting MIL-DTL-29606A in July of 2014 and including qualification requirements of conductors under AS29606 "**Wire, Electrical, Stranded, Uninsulated Copper, Copper Alloy, or Aluminium, or Thermocouple Extension, General Specification for".** This revision also introduced a new class of copper alloy called Extra High Strength Copper Alloy which meets the requirements of High Strength Copper Alloy with a 33% increase in tensile strength.

In 2016, SAE AE-8D released detailed specification sheets utilizing the extra high strength conductor material in the extruded cross-linked Ethylene-Tetrafluoroethylene (XL-ETFE) product line and the PTFE/Polyimide tape wrapped product lines and requested that the material class be added to the approved shield types listed in WC27500. In November 2017, SAE AE-8D released AS6324 **"Verification of New Conductor Alloys for AS29606 Conductors Qualification"** to establish an industry protocol on how to qualify new alloys for aerospace electrical applications.

Table 3 provides the properties for standard materials followed by Table 4 which provides the properties for hybrid materials. The materials presented represent the ten primary classes of braid materials used in aerospace applications today. Stainless steel and aluminium do not have an outer coating or plating material. All of the other materials are typically coated with either tin, nickel, or silver. Figure 1 displays the relative performance of the standard material types and Figure 2 displays the hybrid material types evaluating density, tensile break strength, conductivity and maximum continuous temperature rating.

The development of new materials for braid applications has changed the evaluation dynamic for designers of aerospace applications. Applications which are more concerned with EMI/EMC threats, weight and volume constraints and less concerned with mechanical robustness and lightning strike considerations have opted to use smaller gauge strands in soft copper, copper alloy, stainless steel, plated copper-clad stainless steel (CCSS), 15 percent copper-clad aluminium (CCA) and non-traditional metal coated fiber materials.

Table 3: Properties of Standard Materials in Soft Temper

Material	Type	Density (g/cc)	Conductivity (IACS)	Tensile (ksi)	Temp. Rating (highest)
Copper	Soft	8.9	100%	32	260ºC
High Strength	Percon 24	8.9	90%	60	260ºC
Extra High Strength	Percon 28	8.9	85%	80	260ºC
Ultra High Strength	Percon HS-95	8.8	63%	95	260ºC
Stainless Steel	Uncoated	8.0	2.5-2.9%	70-120	260ºC
Aluminium	Uncoated	2.6-2.8	61%	18	175ºC

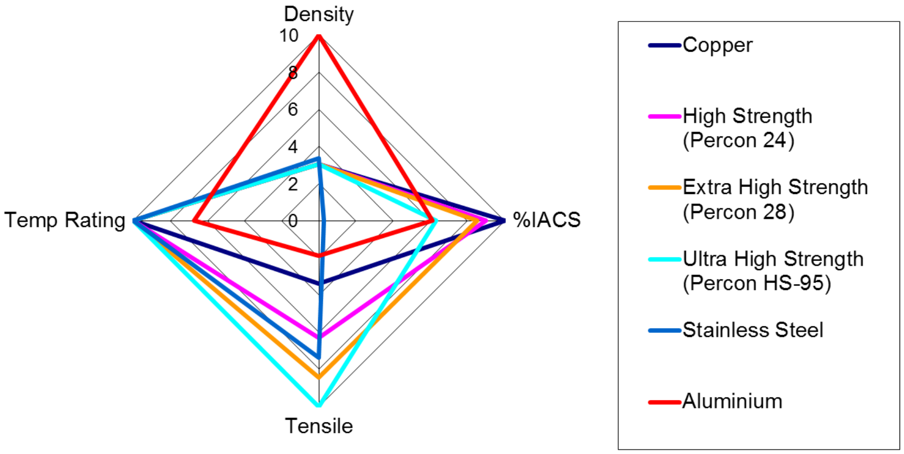


Figure 1: Relative Properties for Standard Materials

Table 4: Properties of Hybrid Materials

Material	Type	Density (g/cc)	Conductivity (IACS)	Tensile (ksi)	Temp. Rating (highest)
Stainless Steel	Ni-Coated Cu-Clad	8.2	35%	70	260ºC
Aluminium	Copper-Clad (15%)	3.6	68%	20	175ºC
PBO	Nickel Coated	3.9 (2.0-5.0)	6.5%	590	220ºC
Kevlar®	Nickel Coated	3.1 (2.0-5.0)	4.5%	310	200ºC

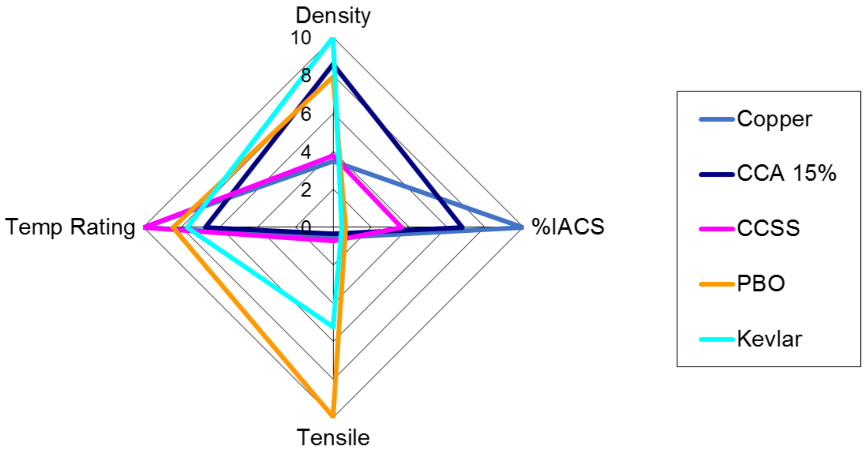


Figure 2: Relative Properties for Hybrid Materials (incl. Copper)

These new materials have been successfully integrated into space, missile, unmanned vehicles, medical patient monitoring systems, and intelligent clothing applications. Smaller gauge materials (primarily copper and copper alloys) have also been successfully incorporated into Coax, Triax, Quad and high speed data cables in both MIL-DTL-17 **"Cables, Radio Frequency, Flexible and Semirigid General Specification for "** and AS6070 **"Aerospace Cable, High Speed Data, Copper".**

PERFORMANCE CHARACTERISTICS

This section will examine the basic performance characteristics of the various material classes. Since plated soft copper is the baseline for braid materials and is very well understood, this paper will not spend time defining its characteristics. Copper alloy, stainless steel, copper-clad stainless steel, aluminium, copper-clad aluminium, PBO and Kevlar based options will be described in more detail.

High Strength Alloy

In the late 1960's as aerospace designers moved to smaller gauge conductors to save mass and volume, high strength alloy (copper alloy 135) was introduced to provide higher tensile break strength than traditional soft copper. A tensile break strength greater than 21 pounds was needed for 24 gauge conductors in order to meet the demands of fabrication, installation, maintenance and a 20 year life cycle.

Alloy 135 (C18135) is a cadmium/chromium copper alloy which offers high conductivity and tensile break strength. The high strength alloy classification of this material was standardized in ASTM B624 with a minimum 85% IACS and 60 ksi (ksi, formerly kpsi, thousands of pounds per square inch) tensile strength. The alloy has been widely used in aerospace applications for 24 gauge and smaller conductors and for metal braids for the past 45 years. Legacy high strength alloy specifications in AS22759 use this material class for 20 gauge through 30 gauge constructions.

Fisk Alloy was the first alloy producer to introduce and qualify a RoHS compliant equivalent high strength alloy (Percon 24) to copper alloy 135 while removing the cadmium content. The material class of high strength alloy was included in the initial release of MIL-DTL-29606 and was part of the word-for-word conversion to AS29606.

Ultra High Strength Alloy

Ultra high strength alloy (CS-95) was introduced on the McDonnell-Douglas A-12 program in 1990. Alloy CS-95 and HS-95 are standard nickel/beryllium copper alloy (C17510) which is processed to offer moderate conductivity of 63% IACS and superior tensile break strength of 95 ksi. This class of alloy is now produced by multiple sources to create a competitive landscape.

The purpose for the material development was the Navy requirement that 26 AWG conductors used on the program needed the same minimum 21 pound tensile break strength to conform to the requirements established for 24 AWG conductors with the introduction of the high strength alloy material. The 26 gauge high strength alloy equivalent had a break strength of 14.2 pounds.

Many programs did not approve of the reduced conductivity to achieve the improved tensile break strength and chose to use the high strength alloy for 26 gauge and smaller applications. Although the A-12 program was eventually cancelled, the ultra high strength conductor became a requirement for 26 gauge constructions in AS22759/81, /82, /89, /90, /181, /182. /189 and /190. The 24 gauge and larger constructions in these detailed specifications still used the high strength alloy material.

Extra High Strength Alloy

In 2014, a new copper alloy was introduced called Extra High Strength Copper Alloy with 85% IACS and 80 ksi tensile break strength. The performance characteristics allow direct replacement of high strength alloy with a 33% improvement in tensile break strength and improved flex life. This product was developed by Fisk Alloy with the product designation of Percon 28.

This new conductor class has been widely accepted by design engineers to address the weaknesses of both high strength alloy (lower tensile strength in small gauge sizes) and ultra high strength alloy (reduced conductivity). It replaced both high strength and ultra high strength alloys in AS22759/55, /56, /57, /58 (XL-ETFE), AS22759/93, /94. /95, /96 (PTFE/polyimide tape wrap) and AS22759/193, /194, /195, /196 (smooth PTFE/polyimide tape wrap) insulated wire constructions.

NEMA WC27500 has been requested to include the new detailed sheets into the specification as well as adding the extra high strength material as a shielding option.

Stainless Steel

Uncoated stainless steel has been used as a braiding material in cable assemblies for decades. MIL-C-27500F dated 3 October 1983 includes stainless steel braid (shield symbols "F" and "Z") material description QQ-W-423, **"Federal Specification Wire, Steel, Corrosion-Resisting"**, form I (round), composition 302, condition A (annealed). The latest version of WC27500 includes the same shield symbols for uncoated stainless steel round with material requirements ASTM A313, **"Standard Specification for Stainless Steel Spring Wire"**, which includes types 302, 304, 305, 316, 324 and 327. WC27500 does not restrict the composition or the condition of the stainless steel prior to shielding.

The primary benefits of uncoated stainless steel is the higher tensile break strength and slightly lower density when compared to copper. The primary disadvantage is the reduced conductivity of 2.5% to 2.9% IACS. Stainless steel is typically used as harness armouring in high impact areas like landing gear harnesses. It is not typically used as an EMI/EMC barrier due to its poor conductivity. Current applications of uncoated stainless steel have established the minimum strand size to 40 gauge.

Stainless steel materials can also be clad with copper and coated with either silver or nickel to improve conductivity. A shielding material using 46 gauge nickel or silver coated copper-clad stainless steel (316L) is currently being used as a cable and harness braiding option. This particular configuration offers significant volume and weight savings while improving the material conductivity to around 36% IACS for nickel coated version and 51% IACS for the silver. The material also offers a higher 70 ksi tensile break strength versus the 32 ksi of soft copper.

Aluminium/Copper-Clad Aluminium

Copper-clad aluminium (CCA) wire was introduced around 1974 and is covered by ASTM B566, **"Standard Specification for Copper-Clad Aluminium Wire"**. The standard configuration for aerospace applications is 15 percent copper and 85 percent aluminium by volume. This material has a conductivity of 68% IACS and a tensile break strength of 20 ksi. Aluminium has a material conductivity of 61% IACS and a tensile break strength of 18 ksi. Aluminium and copper-clad aluminium have been used in aerospace for large gauge power feeders to save weight since the density of the materials are nearly 60% less than copper. Since the current carrying capacity of both aluminium and copper-clad aluminium are lower than the same volume of copper, it requires the conductor to be larger to carry the same load of current. The mass/volume trade-off is very advantageous for the airframe, although there is a reduction in the maximum temperature rating of the conductor. The copper layer of copper-clad aluminium also improves the shielding performance at higher frequencies where skin effect is the dominant characteristic. Industry concerns with both materials include termination methods, temperature rating and flexure endurance/life.

Nickel and silver plated copper-clad aluminium has been used in conductor and shield braid applications. The plating provides protection to the copper preventing oxidation. Concerns with the nickel plating cracking have been documented on this material class. Experiences with small gauge size nickel plated copper-clad aluminium conductors being terminated into AS39029 crimp contacts have garnered limited acceptance. Processing limitations of this material have prevented size reduction below 40 gauge. The mass/volume characteristics of the material make it a good option for aerospace and space usage. Also the silver plating improves shielding performance at very high frequencies.

Metalized Polymers

Metalized polymers are based on the concept of the polymer core providing the flexibility and tensile strength while the metal coating provides the conductivity and EMI/EMC protection.

This alternative market was first developed by DuPont with the introduction of Aracon® around 1998. Aracon® is metalized Kevlar® (aromatic polyamide) fiber (54 AWG) sold on bobbins in typical textile sizes of 200 and 400 denier. Aracon® is available in either nickel or silver coated varieties and is sold by the foot. The material has excellent tensile strength of 320 ksi but very poor electrical conductivity at 4.5% IACS for nickel coated product.

The primary benefit of the metalized Kevlar® material is that it resembles a textile material when overbraiding an electrical harness or circuit. A single end of 200 denier product spreads out and forms an equivalent cross section of 0.020 by 0.004 inches when braided on a cable or a harness. Due to this characteristic, optical coverage is typically 100% and shielding effectiveness above 100 MHz is significantly improved over 36 gauge plated copper.

Another material being used in braid applications is a product based on PBO (Zylon®) fiber. Zylon® (poly(p-phenylene-2,6-benzobisoxazole) is a trademarked name for a range of thermoset liquid-crystalline polyoxazole.

The braid material is constructed from a 56 gauge nickel or silver coated PBO. The fiber has a very high tensile break strength of 590 ksi with low conductivity compared to soft copper at 6.5% IACS for nickel coated product. Due to the small strand size and high strand count, the material fills gaps within the braid structure extremely well which allows improved transfer impedance and shielding effectiveness at frequencies above 100 MHz.

Plating Materials

Metal overbraids used in aerospace harnesses utilize tin, silver, or nickel plating. Each plating material comes with desirable and undesirable characteristics.

Tin plating is the lowest cost plating material. It is easily adapted to both soldering or crimp terminations. Tin plating has a service life temperature rating of 150°C which is the lowest of the plating materials used. The tin oxidizes and forms intermetallics very easily which can affect solderability over the life of the product. It is not thermally compatible with higher temperature heat shrink sleeving materials which may be used as a chafe guard.

Silver plating was the most common material used prior to 1996. It is the most expensive plating material and often increases the cost of the braid by thirty percent. It is easily adapted to both soldering or crimp terminations. Silver plating has a service life temperature rating of 200°C. Silver plated copper is susceptible to both silver oxide and copper oxide formation. Galvanic corrosion of silver plated copper leads to the formation of red plague, while white plague is corrosion of silver plating as a result of fluorine outgassing from the insulation. The thermal rating is high enough to be compatible with most thermally set chafe guard materials.

Prior to 1996, nickel plating was reserved for use in the harshest aerospace environments due to the difficulty of termination. Several red plague incidents in the mid 1990's convinced designers to develop manufacturing methods to easily terminate nickel plated copper braids and conductors. Although not as forgiving as silver or tin, soldering or crimp termination methodologies are now mainstream. The cost of nickel plated material is higher than tin due to the increased difficulty of drawing the strands to size. Nickel plating has a service life temperature rating of 260°C making it compatible with all commonly used jacket or chafe guard materials.

COMPARISIONS

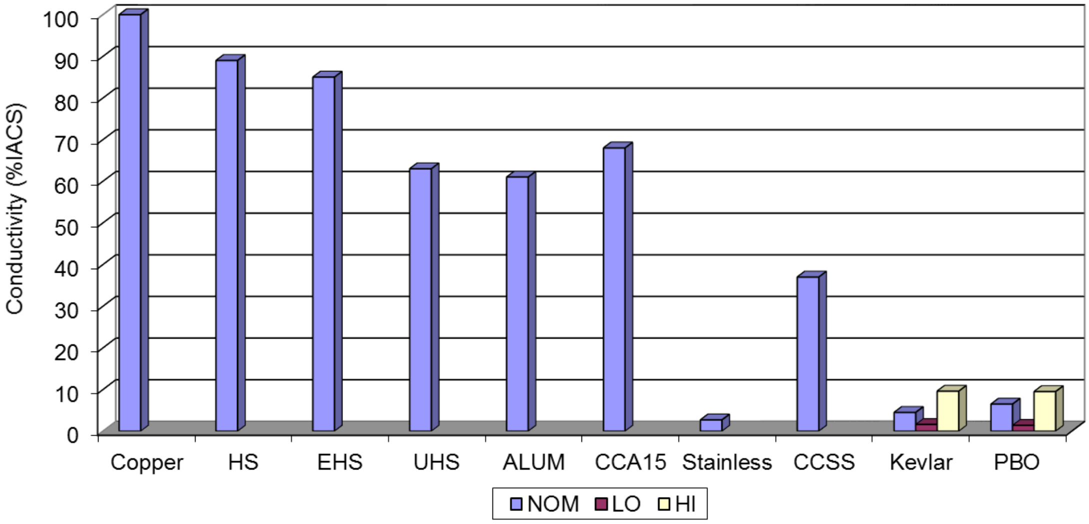
All of the materials discussed in this paper are either available on bobbins for braiding on harness assemblies or as slip-on braids of various core diameters. The primary benefit of material provided on bobbins is that the braid layer is tightly conformed to the harness assembly and material used is dictated by the harness core diameter. The slip-on braids must be larger than the harness core diameter to be able to slide it over the bundle. This evaluation compares standard product with normal nickel plating thickness.

Conductivity

The basic conductivity of equivalent braid strands is strictly a function of metal content and the conductivity of the specific metal/s used. The conductivity of each material can be expressed as a percentage of the International Annealed Copper Standard (IACS. When using this standard, soft copper is 100%IACS, silver is 106%, nickel 24%, 15 percent copper-clad aluminium 68%, and stainless steel (316L) is 2.3%. The conductivity of the alternate braid materials is based on the nominal density provided by the manufacturer and calculating the total metal mass. Copper-clad stainless steel has a conductivity of approximately 36% when plated with nickel.

Metalized Kevlar and metalized PBO have a density range of 2.0-5.0 g/cc, which creates a significant variance in the calculated conductivity of the applied fiber. This large range indicates that the thicknesses of nickel plating can vary significantly as supported by the %IACS.

Figure 3 displays the conductivity of each material. Reduced conductivity of the material adversely affects DC resistance and transfer impedance at low frequencies.



Copper = Soft Copper
HS = High Strength Copper Alloy
EHS = Extra High Strength Alloy
UHS = Ultra High Strength Alloy
ALUM = Aluminium
CCA15 = 15% Copper-clad Aluminium
Stainless = Stainless Steel
CCSS = Copper-Clad Stainless Steel
Kevlar® = Nickel Plated Kevlar®
PBO = Nickel Coated PBO

Figure 3: Conductivity Comparison

Mass

The weight of the shield overbraid is directly related to the size of the braid strand with all other parameters being equal. Since typical metal overbraids consist of 36 gauge copper strands, using 46 gauge or 54/56 gauge material as a replacement should generate approximately a 70 to 80 percent weight reduction. Mass is directly proportional to the diameter of the shielding strand. Instead of using alternate materials which are not standardized in the industry, similar weight savings can be garnered using copper alloys which offer similar tensile break strength while significantly improving conductivity.

Since soft copper and copper alloys have the same density and hence mass, the metal braid weight using different gauge sizes can be compared to the application of the alternative braid materials. Using a 0.250 inch core diameter, weight calculations have been made to examine the effect gauge size has on weight using various materials (Figure 4).

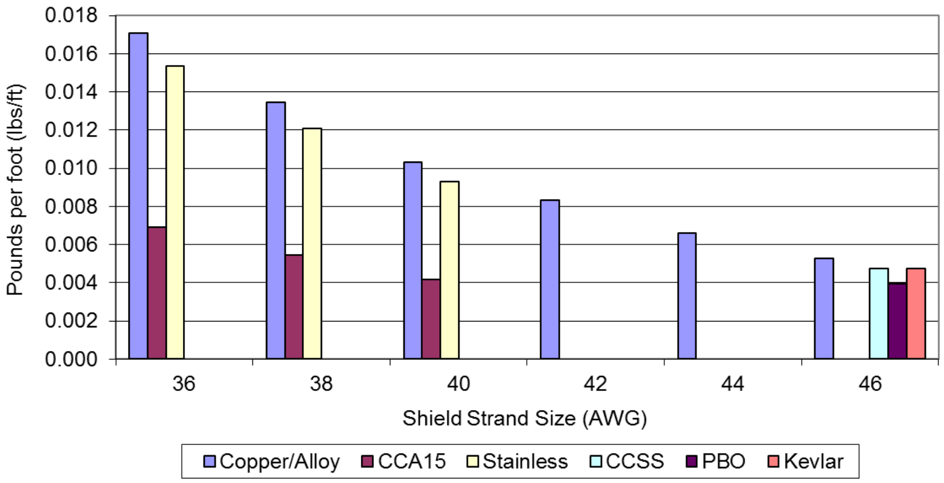


Figure 4: Weight per foot, core diameter 0.250"

The expectation is that the weight of the braid is reduced along with the gauge size. The density of stainless steel is about ten percent less than the copper/copper alloys at the same gauge size and the density of the copper-clad stainless steel is about eight percent less than copper. The mass of copper-clad aluminium is about sixty percent less than copper. The metalized PBO and the metalized Kevlar® are applied in multi-strand denier configurations which does not lend itself to draw direct comparisons to round braid.

Analysis can be divided into two distinct regions. The first region is 36 gauge to 40 gauge. Copper-clad aluminium offers the best weight reduction in this region when compared to 36 gauge soft copper. The copper alloys offer significant weight reduction associated with strand downsizing. Stainless steel offers a small weight reduction relative to copper at each evaluation size.

The second region is 42 gauge to 46 gauge. For 42 and 44 gauge, similar conclusions as the 36 to 40 gauge range can be made for copper alloys. Copper-clad aluminium and stainless steel do not appear in this range due to strand processing limitations. The last gauge size position (46 gauge) provides the relative weight comparison using a 46 gauge copper alloy versus the three alternate materials. Weights for nickel coated PBO, nickel coated copper-clad stainless steel and nickel coated Kevlar® were taken out of the vendors' data sheets and not calculated for this study. For easier comparison of the calculated values, Table 5 displays the weight (lbs/ft) for each gauge size from Figure 4. At 46 gauge the weight impact ranges from lightest, PBO at 0.0040 lbs/ft, to heaviest, copper alloy at 0.0053 lbs/ft. When you compare this to using 36 gauge copper at 0.0171 lbs/ft, all four options provide similar weight savings.

For further illustration, Table 6 details the percent weight reduction relative to 36 gauge copper/alloy. At 46 gauge the relative weight reduction is comparable for each of the four materials, ranging from 69% to 77%.

Table 5: Weight per foot (lbs/ft), core diameter 0.250"

Material	Shield Strand Size (AWG)					
	36	38	40	42	44	46
Copper/Alloy	0.0171	0.0134	0.0103	0.0083	0.0066	0.0053
CCA15	0.0069	0.0054	0.0042			
Stainless	0.0153	0.0121	0.0093			
CCSS						0.0047
PBO						0.0040
Kevlar						0.0048

Table 6: Percent Weight Reduction relative to 36AWG Copper/Alloy (0.250" core)

Material	Shield Strand Size (AWG)					
	36	**38**	**40**	**42**	**44**	**46**
Copper/Alloy	0%	21%	39%	51%	61%	69%
CCA15	60%	68%	75%			
Stainless	10%	29%	46%			
CCSS						72%
PBO						77%
Kevlar						72%

Tensile Break Strength

The low tensile break strength of soft copper was the primary driver in developing high strength copper alloys for use in aerospace interconnect systems. Designers were willing to sacrifice some conductivity to improve tensile break strength. A side benefit of developing these alloys was an improvement in cyclic flex life for the insulated wire. When examining tensile break strength, comparing solid metal strands is very straight forward. The application of this method to the coated fiber materials is a little more difficult in that it does not identify the point of fracture of the metalized outer plating versus the core material. With metal products, continuity is never lost until material separation. With the plated fibers, metal fracture can occur prior to the yield point of the base material. The loss of continuity would significantly degrade the performance of the braid without experiencing fiber breakage. That being said, Figure 5 provides the tensile strength of each material in ksi. The Y axis is displayed in logarithmic scale for clarity.

The tensile break strength of Kevlar® is 10X higher than soft copper and the PBO is 18X higher. The tensile break strength of stainless steel is higher than high strength alloy and lower than extra high strength alloy. The copper alloys provide an 87% to 197% increase in tensile break strength versus soft copper. The stainless steel and non-standard copper-clad stainless steel material (70 ksi) provides approximately 118% higher break strength than soft copper. The lower tensile break strength of copper-clad aluminium (25 ksi) when compared to soft copper (32 ksi) could limit its application where material strength and load bearing of the braid are design criteria.

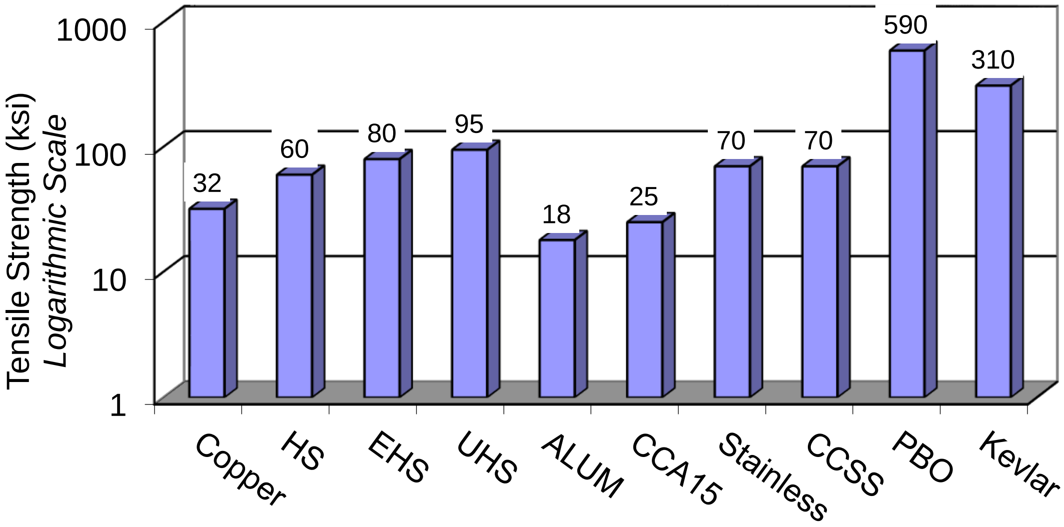


Figure 5: Tensile Strength Comparison

Braid Volume

The next consideration is the amount the braid layer increases the overall diameter of the harness assembly. When considering tight installation dynamics, the braid build up may be a significant design consideration.

A typical 36 gauge copper braid will increase the bundle diameter by about 25 mils (thousands of an inch) or .025". The impact decreases along with the size of the braid strand. At 46 gauge, both the extra high strength copper alloy and copper-clad stainless steel impact the harness by about 7.5 mils. The braid impact for the nickel coated PBO and the nickel coated Kevlar® is about 10 mils. The comparison is displayed in Figure 6.

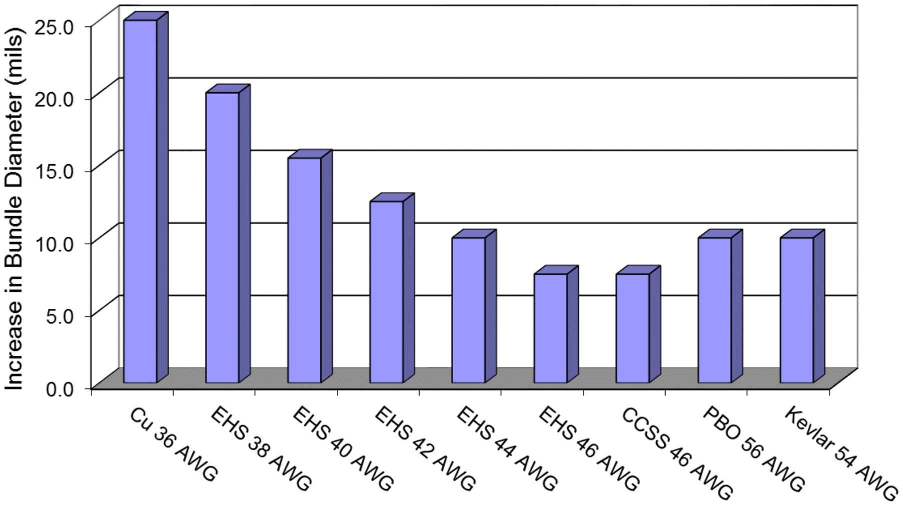


Figure 6: Braid Layer Impact

EMI/EMC Performance

Low DC transfer impedance and DC resistance are strictly a function of metal mass and conductivity. In this environment, the 36 gauge soft copper offers the best of both worlds and would offer the best performance. The copper alloys would provide slightly less performance versus soft copper at the same gauge size due to the reduced conductivity. As the strand size gets smaller, the resistance and DC transfer impedance will increase for all copper and copper alloy configurations as well as any other alloy.

Due to their high electrical conductivity, at frequencies less than 10 megahertz, copper and copper alloy braids will offer superior performance to all alternative material options. The transfer impedance will experience a cross-over based on the influence of skin effect and conductivity of the material between 10 and 100 megahertz. Above 100 megahertz, the influence of skin effect will drive performance. Typically, the smaller the strand size, the better the performance above these frequencies. This effect is the result of multiple factors. The first is that smaller strands in the same coverage have higher surface area exposure versus larger strands. Second, smaller strands create smaller gaps (holes) and windows in the braid structure.

Given the same coating material, either nickel or silver, the 46 gauge constructions in copper-clad stainless steel and extra high strength copper alloy should exhibit similar transfer impedance and shielding effectiveness performance at frequencies above 100 MHz. In theory, the 54 and 56 gauge materials in Kevlar® and PBO could provide better shielding effectiveness in this region, but side by side comprehensive evaluations of all materials have not been performed by independent labs to verify relative performance.

SUMMARY OF FINDINGS

In this section the applications will be divided into two regions. This first region will examine direct replacement of 36 gauge soft copper with copper alloys, stainless steel and copper clad aluminium in 36 gauge to 40 gauge. The second region will examine replacing 36 gauge soft copper with copper alloys and alternate braiding materials in sizes smaller than 40 gauge.

Braid Applications: 36 to 40 Gauge

Harness metal overbraids are typically 36 gauge. As noted before, the wire size is either derived from A-A-59569 or WC27500 depending on the criteria identified in the designer's process specifications. WC27500 does allow for strand size reduction down to 40 gauge. Due to the low tensile break strength of copper-clad aluminium, it would probably need to be limited to 34 gauge in dynamic applications. In static applications it could possibly be used in 36 or 38 gauge as part of a weight reduction strategy. Stainless steel would be limited to applications where conductivity is not a primary design concern, but tensile break strength is more critical. Extra high strength alloy has both high conductivity and tensile break strength making it a strong natural contender for reducing strand size in conventional metal overbraid applications.

Tables 7 and 8 examine the characteristics of the material single end properties for conductivity, tensile break strength and density/specific gravity. These characteristics are applicable for both stranded conductors and braid constructions. The weight in pounds per foot are based on a 0.250 inch braid with 90 percent optical coverage.

Table 7: Properties of Copper, EHS, SS and CCA

Characteristic		**36 AWG**				**38 AWG**			**40 AWG**		
	units	Copper	EHS	SS	CCA	EHS	SS	CCA	EHS	SS	CCA
Conductivity	%IACS	100%	85%	3%	68%	85%	3%	68%	85%	3%	68%
DCR, *SE*	ohms/ft	0.42	0.49	15.37	0.61	0.76	24.00	0.95	1.27	40.00	1.59
Tensile Strength	ksi	32	80	70	20	80	70	20	80	70	20
Break Load, *SE*	lbf	0.80	2.00	1.75	0.50	1.25	1.09	0.31	0.75	0.66	0.18
Density	g/cc	8.9	8.9	8.0	3.6	8.9	8.0	3.6	8.9	8.0	3.6
Weight, *SE*	lb/ft	0.0171	0.0171	0.0154	0.0069	0.0136	0.0122	0.0055	0.0107	0.0096	0.0043
Wt. Red. vs. 36 AWG Cu		0.0%	0.0%	10.1%	59.6%	20.7%	28.5%	67.8%	37.1%	43.8%	74.7%
Temp. Rating *(Max)*		260C	260C	260C	175C	260C	260C	175C	260C	260C	175C
Standard Material		Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes	No

Table 8: Percent difference of EHS, SS, and CCA relative to 36 AWG Copper

Characteristic	**36 AWG**				**38 AWG**			**40 AWG**		
	Copper	EHS	SS	CCA	EHS	SS	CCA	EHS	SS	CCA
Resistance	100%	118%	3704%	147%	183%	5783%	230%	306%	9639%	383%
Tensile Break	100%	250%	219%	63%	156%	136%	39%	94%	83%	23%
Weight	100%	100%	90%	40%	80%	71%	32%	63%	56%	25%

This comparison illustrates that copper-clad aluminium offers significant weight reduction with moderate degradation in resistance and very poor tensile break strength. The tensile break strength will limit the reduction strategy due to the increased risk of strand breakage. Copper-clad aluminium's current carrying reduction also impacts a direct replacement with soft copper. Design strategies using copper-clad aluminium typically use a larger strand size to address the current carrying limit as well as the tensile break strength deficiency. Using a 34 gauge strand to replace a 36 gauge soft copper strand recovers the current rating, provides 116% of the tensile strength and a 50% weight reduction when compared to the soft copper strand.

Extra high strength copper alloy (Percon 28) offers the best blend of characteristics. Figure 8 offers a comparison between

Percon 28 in 36, 38 and 40 gauge and soft copper in 36 gauge. Resistance and tensile strength are based on single end performance. Product cost is based on multiple ends on bobbins for cable and harness braiding. Weight is based on a 0.25 inch core braided with 36, 38 and 40 gauge strands with 90 percent optical coverage.

The superior tensile break strength of extra high strength copper alloy reduces the probability of strand breakage at 36 and 38 gauge and nearly matches 36 gauge soft copper at 40 gauge with 94% of the soft copper's performance. Conductivity of the extra high strength is 85% of soft copper so the impact of size reduction results in 55% at 38 gauge and 33% at 40 gauge when compared to the 36 gauge soft copper strand. Overbraid weight reduction opportunities of 22% at 38 gauge and 40% at 40 gauge are expected. Given the Percon 28 performance characteristics, strand size reduction strategies result in maintaining high tensile strength, significant mass reduction with manageable resistance increases in both conductor and braid applications.

Stainless steel provides improved tensile strength with reasonable weight reduction but very low conductivity which would make the material suitable for applications where conductivity is not a major design constraint or where EMI/EMC protection is not critical. Design applications for stainless steel would include requirements for a high tensile strength member or harness armouring for impact protection. In applications where EMI/EMC protection is needed, a second layer of copper braid or foil place beneath the stainless steel is typically used. Use of a single layer of the extra-high strength copper alloy shield may be able to simplify this complicated process.

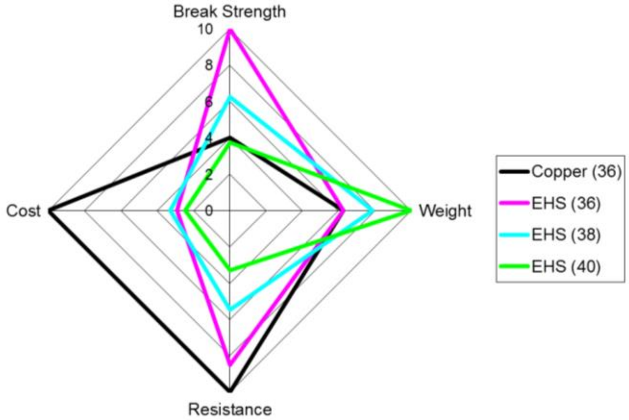


Figure 8: Relative Properties of 36 AWG Copper versus EHS

Braid Applications: Smaller than 40 Gauge

Braid and conductor applications smaller than 40 gauge are examined as non-standard designs. Specifications AS29606 (conductor), WC27500 (cable) or A-A-59569 (slide on braid) do not provide requirements for this strand size region.

Strand size reductions in this region have been used for specialized cases where mass, volume and high frequency EMI/EMC protection are critical design requirements and DC resistance, tensile break strength and cost are secondary concerns. The materials offered in this region are typically vendor specific products.

Tables 9 and 10 examine the characteristics of the material single end properties for conductivity, tensile break strength, and density/specific gravity. These characteristics are applicable for both stranded conductors and braid constructions. The weight in pounds per foot are based on a 0.250 inch braid with 90 percent optical coverage.

The performance expectation of extra-high strength alloy Percon 28 in the 42 gauge to the 46 gauge region is very predictable. The three non-standard material options offer unique performance characteristics with a reduction in conductivity while significantly reducing volume and mass.

Table 9: Properties of 36 AWG Copper, and finer gauge EHS, CCSS, PBO & Kevlar

Characteristic		**36 AWG**	**42 AWG**	**44 AWG**	**46 AWG**		**50 AWG & Smaller**	
	units	Copper	EHS	EHS	EHS	CCSS	PBO	Kevlar
Conductivity	%IACS	100%	85%	85%	85%	36%	7%	5%
DCR, *SE*	ohms/ft	0.42	1.95	3.04	4.95	11.79	64.76	93.55
Tensile Strength	ksi	32	80	80	80	70	590	310
Break Load, *SE*	lbf	0.80	0.35	0.23	0.13	0.11	N/A	N/A
Density	g/cc	8.9	8.9	8.9	8.9	8.2	3.9	3.1
Weight, .250" braid	lb/ft	0.0171	0.0083	0.0066	0.0053	0.0049	0.0040	0.0048
Wt. Red. vs. 36 AWG Cu		0.0%	51.5%	61.4%	69.0%	71.4%	76.6%	71.9%
Temp. Rating *(Max)*		260C	260C	260C	260C	260C	220C	200C

Table 10: Percent difference of fine gauge EHS, CCSS, PBO and Kevlar relative to 36AWG Copper

Characteristic	**36 AWG**	**42 AWG**	**44 AWG**	**46 AWG**		**50 AWG & Smaller**	
	Copper	EHS	EHS	EHS	CCSS	PBO	Kevlar
Resistance	100%	470%	733%	1193%	2840%	15605%	22542%
Tensile Break	100%	44%	29%	16%	14%	N/A	N/A
Weight	100%	49%	39%	31%	29%	23%	28%

The nickel plated copper-clad stainless steel is a very unique product and not covered by any aerospace standard. The benefit of the copper cladding is a significant improvement in conductivity versus stainless steel with a slight increase in weight.

The PBO and Kevlar coated materials behave more like a textile braid than a metal braid due to their very small diameter size. This offers excellent coverage and flexibility. Due to their small size and bunching of individual fibers into a denier core, tensile break strength is not measurable on a single strand.

Figure 9 depicts the relative performance of each material class by gauge size. The characteristics of the material single end properties for conductivity, tensile break strength and density are applicable for both stranded conductors and braid constructions.

The weight in pounds per foot are based on a 0.250 inch braid with 90 percent optical coverage.

Performance of the materials noted in this gauge size range provide some interesting properties. All of the materials will exhibit significantly improved flexibility over traditional braid options. The small strand size will also provide improved shielding effectiveness and transfer impedance at frequencies above 100 MHz. The extra high strength copper alloy option provides significantly better conductivity while providing slightly higher tensile break strength over the copper-clad stainless steel material. All of the options provide a significant mass and volume reduction over 36 gauge copper. These materials may not be suitable for environments where low frequency EMI/EMC threats exist or there is a potential for lightning strike.

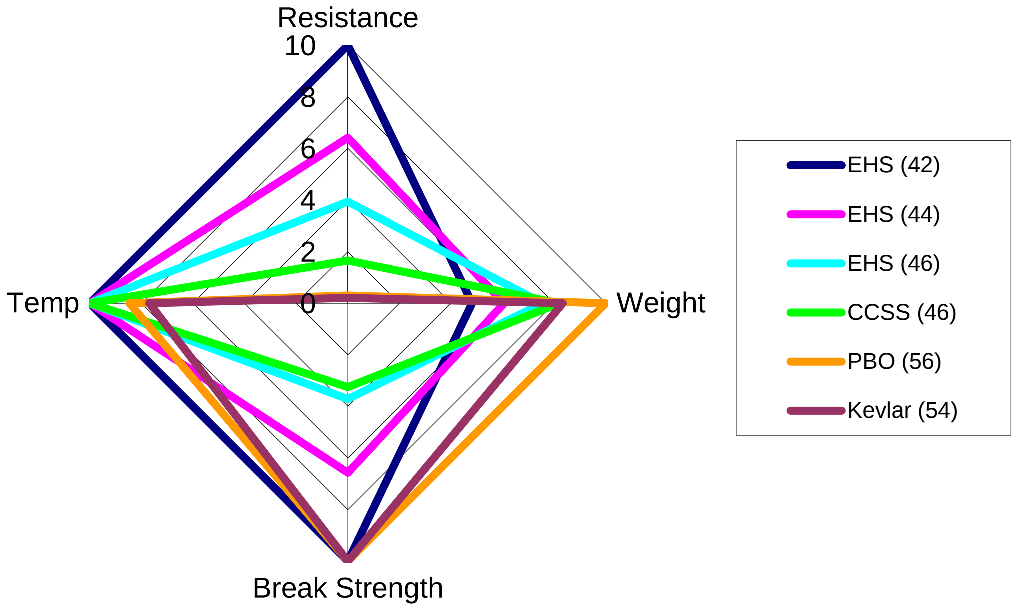


Figure 9: Relative Properties of fine gauge EHS, CCSS, PBO & Kevlar

CONCLUSION

The selection of material and strand size for metalized braid and overbraid applications are made by the design authority who knows the risks and threats of the application the best. For general purpose aerospace applications, the use of the tables in NEMA WC27500 and guidance from A-A-59569 have provided a well proven design method for meeting the threats present.

The 36 through 32 gauge plated copper materials offer significant mechanical and electrical margin for long term survival in airframes which will be used for 50 plus years. The mass and volume penalty to the airframe for using large gauge soft copper braid material is now being examined to find the best mix of properties for the specific application. RoHS compliant copper alloys are now being considered as a valid replacement providing superior mechanical strength while sacrificing slight electrical conductivity relative to copper.

Newer applications which incorporate smaller harness designs and do not have the lightning strike or long term maintenance activities to address have migrated to smaller strand sizes. This saves weight and volume while improving the shielding effectiveness against high megahertz and gigahertz sources.

The use of alternate braid materials, copper-clad stainless steel, coated Kevlar, and coated PBO, have dominated this space for the past 20 years. As more and more applications need this type of enhanced performance along with cost reduction considerations, the use of Extra High Strength copper alloy qualified to AS29606 can provide similar EMI performance with greatly improved conductivity and comparable tensile break strength properties.

ABOUT THE AUTHORS

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Brian Gerard is Director of Technology at Fisk Alloy, Inc. where he has been in charge of product and alloy development efforts and collaborated with industry partners to advance what is possible in the world of alloy wire since 2015. Prior to joining Fisk Alloy, Brian was a metallurgist for the US Army based at Picatinny Arsenal in New Jersey. A metallurgist by trade, Brian received both a Bachelors and Masters of Science in Materials Science and Engineering from Lehigh University. Brian is excited to join his colleagues in the SAE Wire and Cable proceedings and grateful for the opportunity to present this paper.

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About Fisk Alloy

Fisk Alloy Inc. develops and produces copper alloy wire for high-performance applications. Our product lines; high precision shaped wire for connector and electronic parts, RoHS compliant copper alloy conductors for electrical cables and braids (Percon), beryllium copper fine wire, high performance and RoHS machinable alloys are found in industries such as aerospace, medical, semiconductor, automotive and electronics. Our product is wire but our business is in innovations that have made a difference in these markets over the past five decades.