Design Tips and FAQ for High Performance Dual Rated, (For Both Aluminum and Copper Wire) Mechanical Type, (Just Tighten the Screw) Reusable, Solderless and Crimpless Wire Connectors,

Why use Aluminum Mechanical Screw Type Wire and Cable Connectors?

1. Mechanical Connectors may be installed with standard electrician's tools.
2. Mechanical Connectors avoid the costly and bulky compression tools and collets for crimp type connectors.
3. End users (customers) prefer the simplicity of "insert the wire, fasten the screw".
4. Dual Rated Connectors give the customer the option to use aluminum or copper wire & cable.
5. Mechanical Connectors can accommodate a wide range of wire sizes and classes to suit different current load applications with the same connector.
6. The wire can be changed by the customer without loss of the connector.

Why Design for Aluminum wire?

The interest in using aluminum wire is driven by the much lower cost and weight of aluminum wire and connectors (3 to 1 lighter). Aluminum wire and connectors are used extensively for electrical distribution by utilities due to its superior economics for power delivered per unit cost.

In recent years copper has increased 3-4 times in cost whereas aluminum has only risen 1.5 to 2 times. In the long term, an even more favorable cost ratio is likely to prevail based on global availability and demand for these raw materials. Bauxite, the raw material to make aluminum is one of the most abundant materials on Earth while copper sources are limited to a few countries worldwide, which limits the ability of copper capacity to expand to keep pace with increasing real world demand.

The relative cost per pound puts aluminum at about 1/3 the cost of aluminum by weight. In addition, that "1/3 the weight" savings, even when offset by aluminum having 40-50% the IACS conductivity of copper, creates an overall cost effectiveness of about 4 to 1 in favor of aluminum for current carrying use.

In addition to its economy, aluminum is easier and less costly than copper to machine or form into complex shapes for sophisticated design functions.

The large North American market is accustomed to using both aluminum and copper wire to suit the particular application. Increasingly copper materials are being replaced by aluminum for dry electrical applications such as industrial, commercial and residential control panels.

How to Pass the UL486 Heat Cycle Test?

Designing a Dual Rated (suitable for both aluminum and copper wire) mechanical (screw type) industrial wire connector requires that a complex array of factors to be taken into account. Wire stranding types, materials, minimum wall thicknesses, expansion rates, conductivity, plating and conversion coatings, lubrication treatment (friction coefficient), corrosion performance, thread pitch, screw diameter, screw nose design (wire indentation), screw tightening drive means, wire hole configuration and other aspects of the aluminum body design such as extrudability, cooling optimization, planned mechanical elasticity and expected permanent creep, are all factored in.

UL requires that all connectors for aluminum wire to be tested under a long term on-off cycle test. This test checks for loosening of the "gas tight" wire joint by simulating the real world thermal expansion/contraction cycles of heating and cooling. Designs goals are to reduce the potential relaxation of the wire joint pressure to prevent failures from poor electrical and heat conductivity from reduced contact pressure and subsequent joint oxidation.

The key design requirement for dual rated mechanical connectors is that the body of the connector be made from aluminum in order to achieve a satisfactory test result with aluminum wire during the long term heat cycle test in UL486A-B (or Canadian standard C22.2).

This Wire Connector test is performed with higher than normal current flowing to extend the connectors stress levels in an artificial aging or fatigue test involving a 1000 repetitive cycles.

<u>Is Steel or Aluminum Right for Electrical Screws in Aluminum Body Connectors?</u>

The material chosen for the screw will usually be aluminum for larger size aluminum wire connectors but may be of steel for smaller connectors.
The rationale for using aluminum on larger sized wire connectors is that the thermal expansion rates of aluminum (wire or connector body) and steel (screws) are too dissimilar, causing problems with aluminum wire. The crossover point to use aluminum screws is somewhere between screws of 5/16 inch diameter and 5/8 inch diameter. Using can steel become problematic at 7/16 inch diameter and above in aluminum body connectors. Performance of the design can be lowered to the extent that differential expansion issues for a given size and design of connector are not sufficiently considered.

| TYPICAL SCREW SIZES USED IN UL 486 A-B MECHANICAL ELECTRICAL CONNECTORS | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| #10 | #12 | 1/4 | 5/16 | 3/8 | 7/16 | 1/2 | 9/16 | 5/8 | 11/16 | 3/4 | 13/16 | 7/8 | 15/16 | 1 |
| SCREW MATERIAL GENERALLY USED FOR ALUMINUM BODY MECHANICAL WIRE CONNECTORS | | | | | | | | | | | | | | |
| STEEL | | | STEEL? OR ALUMINUM? | | | | | | | | | | | |
| | | | STEEL? OR ALUMINUM? | | | | | | ALUMINUM | ALUMINUM | | ALUMINUM | | |

Even if a design can pass UL testing, its ultimate robustness and longevity may be less than optimal if not designed conservatively. Passing UL486 still does not guarantee a particular life expectancy so OEMs also look at long term customer satisfaction and the likelihood of the design reserve required for customers' heavier than anticipated use of their product. Many OEM's expect both lower cost (less metal, lower cost metal, and the ability of the design to be easily mass produced at low cost) and tougher than standard performance criteria, all at the same time. Additionally, SCCR (Short Circuit Current Rating) testing and use of flex or flexible wire (finely stranded wire) has increased the complexity of mechanical connector design compared to traditional UL486 testing alone. Thoughtful design can help to optimize these multiple and sometimes conflicting factors.

## Why are some Connectors Heat Rated at "7" (75C) and Some at "9" (90C)?

Other factors for the choice of screw material are related to the heat rise performance of the connector. UL486B heat ratings of 90 C degrees are more easily obtained with an aluminum screw than steel as aluminum has more than twice the heat and electrical conductivity of steel. In addition aluminum screws have the same expansion rate as an aluminum body and aluminum wire.

The cost of steel and aluminum as the raw material for screws is not as different as one might think from the difference in metal cost per pound due to the nearly 3 to 1 savings in weight for the same screw volume. Aluminum screws can be cold formed using net metal methods in the same way as cold formed steel screws.

In cases where the connector body mass is rather minimal, the choice to use steel for the screw may drop the performance in terms of heat rating of the wire that may be used with the connector from 90C to 75C wire.

## What does CU7AL and CU9AL mean?

The CU and AL refer to the connector being "dual rated" for both aluminum and copper wire and the 7 or 9 refer to the heat rating of the wire insulation. A "7" = 75C and a "9" = 90C. Clearly, the hotter that the wire is allowed to run in conformance with its insulation temperature rating and current load, the hotter the connector will run, or the less heat that the hotter wire will help to drain away from the wire connection.

When a "9" or 90 Celsius heat rating is required for a new connector design, for use with 90C wire, it must be made to run cooler (it will have larger mass/cooling area) for the same current flow than a "7" rating would have to be. UL will require the test current to be higher for a "9" rating connector than a "7" heat rating. At the same time the total temperature rise and the stability of the temperature must meet the same UL criteria as for a "7" being tested at lower current.

The least amount of a given material that can be used to engineer a high performance, low cost connector is limited by the convection surface area, the thermal mass, and the total joint resistance. The latter also has to be stable mechanically to avoid significant changes in contact resistance throughout its expected operating life.

## What Design Features Give Good Wire Pull Out Performance?

The force and pressure on the wire is a function of many mechanical parameters that affect wire pull out performance, as well as some other performance characteristics.

The chart below shows a typical force curve to accomplish satisfactory wire pull out to pass UL wire pull out tests.

The actual force is not easily known as the input "setting" is Inch-pounds of torque on the screw, which then translates into force on the wire, after a large factor for frictional losses. Screw diameter, material, plating, lubricity treatment, thread pitch, thread form, and screw and connector shape can be used to optimize the end result.

Extensive empirical testing is usually required to optimize the design parameters.

Connector manufacturers have learned what combinations of these variables can be most effective and can help the customer with suggestions for new design requirements. UL wire pull out performance may also need to be enhanced to allow for the desired SCCR (Short Circuit Current Rating). This is a test which discovers if the extensive "whiplash" from the EMF (Electro Motive Force) that occurs when tens or hundreds of thousands of amps are passed through the wire in the Earth's magnetic field, can cause the wire to pull out or break the connector mounting means. The extreme but short duration spike of current and also creates heat before fuses or circuit breakers can disconnect the short circuit.
Typically, plastic components and mounting fasteners to plastic will fail before a robust, all metal mechanical connector but the higher SCCR ratings still need to be considered at the connector design and there are useful design features can be used to increase SCCR performance in a mechanical connector.

<u>What Is the UL standard Torque Table?</u>

Many mechanical (screw type) connector designs are built around UL486 standard torque tables for various slotted screw slot sizes and hexagon socket drive sizes. The origin of this was apparently intended to base the tightening torques on what might be reasonably achieved with a screw driver or Allen (hexagon) socket wrench or key of a given size.
This approach was probably based on the assumption that installers would not use a torque wrench to tighten screws but the standard hand tool related to the drive means. However, the professionalism of the workplace today is such that torquing a connector to the correct, test verified user torque is not unreasonably expected. Torque wrenches with interchangeable drive bits are readily available.

<u>What are "Assigned Torques"?</u>

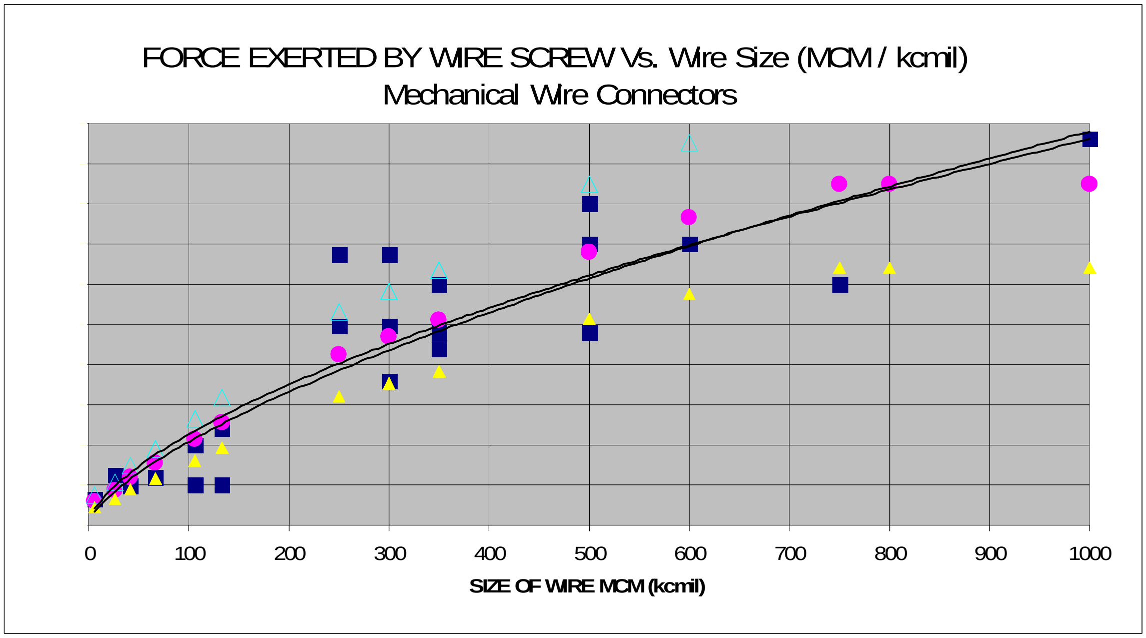
Optimized "assigned torques" can give a connector more end use functionality. For example, it is unlikely that a small wire benefits from the same high torque that a large wire requires and may risk cutting the smaller wires. Consequently a connector may need to have torques carefully selected, rather than arbitrarily, per the UL tables.

Developing optimum torques for each wire size, rather than a one-torque-fits-all approach benefits both the designer and user in terms of improved flexibility and functionality. UL calls these "Assigned Torques".

This benefit of greater design flexibility for mechanical wire and cable connectors permits a more varied range and scope of wire compatibility, with enhanced in-service performance including the inclusion of International wire connector standards like IEC along with North American UL and CSA, NEC and ANSI standards.

How Can Pull-Out Force Performance Be Increased?

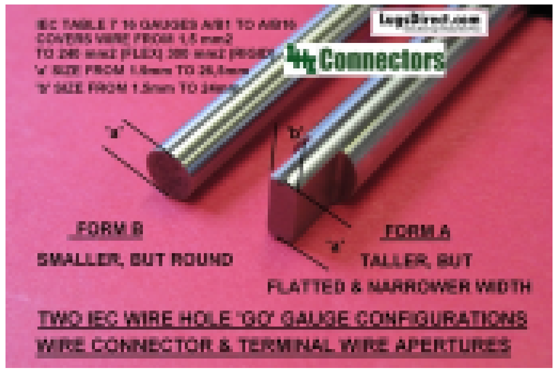
Wire pull out performance may be enhanced by using various wire gripping features like ribs, scallops, serrations, holes, trepans, and screw nose geometry. Overly aggressive wire gripping features may be counter productive if the feature causes the wires to be cut or broken during the dynamic wire secureness test, which could result in a failed test.
In short, the "right" force to maintain a wire securely in a mechanical connector can vary significantly based on many design conflicting factors.




What Affects the Wire Hole size?

The wire hole sizes for standard North American industrial wire (solid and stranded class B and C) are well established and have been used satisfactorily for years. However if the maximum wire size is needed in a "flex" wire (fine stranded flexible wire) a larger wire aperture size is often needed. Metric wire sizes may be inside or outside the conventional range of AWG/kcmil wire sizes. If the nearest metric wire is outside the AWG/kcmil range then it will need to be tested in order to be included in the wire range.

Metric fine stranded flex wire and various US fine stranded flex wire classes also have to be tested to be included in a connector's permitted range of wire classes. The reason for this is that stranding can change how the wire performs in the connector.
The design of UL type connectors to also include IEC standards will tend to change the final size of the wire hole to accommodate both Metric wire sizes and the IEC regulations on the minimum size and shape of a wire hole for a certain size of Metric wire.




Why is Flexible Wire becoming more commonplace?

Generally, for stationary panels, "flex" wire is used for convenience of routing and bending the wire by hand (no pipe bender needed).
This has created the need to consider testing connectors for flex wires at the same time as standard industrial "semi rigid" stranded wire still widely used for electrical panels.

In other cases flex wires are used for moving applications. Connectors must be specially designed for a wire that moves constantly. However, most industrial/commercial applications involve stationary panels, and the selection of wire types to include flex wires is driven mainly by the desire of panel shops and users to use flex wire for convenience. Flex wires are usually copper and cost more than standard industrial "Semi-Rigid" stranded wire due to the fine wire stranding fabrication costs and larger insulation diameters.

What affects Heat Dissipation in Wire Connectors?

Extruded Aluminum can be quite a useful medium for aiding heat dissipation in wire connectors. Where space permits, extruded fins and other surface area enhancing features may be added to the design with very little increase in cost.

Most heat generated in a wire connector is dissipated by air convection. Generally, the amount of radiated heat (infra red) from a normal wire connector running temperature will be minimal due to the relatively modest peak temperatures that are encountered with such connectors. We know, by contrast, that the Sun radiates

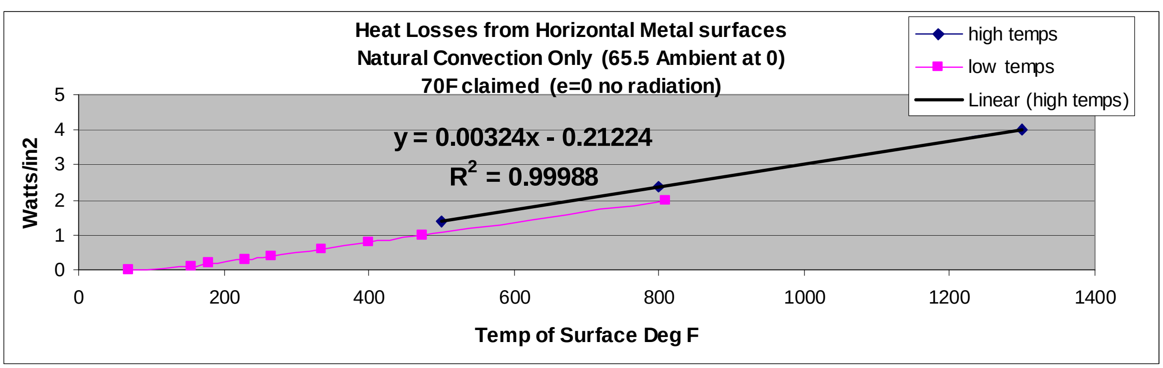
100% of its heat dissipation but has to be extremely hot to do it at such high levels. No air convection takes place in a vacuum.

Consequently, the more that designs are able to incorporate air contact and air flow, the cooler running they are likely to be. Aluminum is the most common material used for heat sinks and heat exchangers in power electronics and automotive cooling because of its ability to be formed into surface area enhancing fins and its low cost for a material that conducts heat well.

The linear heat loss chart below shows that only changing Surface Area or increasing Temperature will increase heat flow from a metal surface in air.
The temperature rise will limit itself as the connector temperature increases, because heat dissipation in watts will increase. However if that stabilized final temperature is too high for the design, the surface area has to be increased to bring it down.
Forced air (fans) are commonly used in electronics applications to save space, weight and cost but in industrial panels, only convectional air circulation within the enclosure is permitted for the ultimate in reliability.

## Where Does the Heat Come From In a Connector?

The heat input for a connector comes from the electrical Watts converted to heat at the wire connection from resistance to current flow. That resistance should remain stable after a settling in period if the design is robust.
If during the UL486B heat rise test or UL486B current cycling test, a significant increase in the electrical resistance of the connection would take place, more heat will be produced in the connection for a substantially similar current level. If it does not stabilize, this would likely result in a thermal runaway situation. As resistance R rises, then Watts ($W = I^2 \times R$) increase in proportion to R, potentially creating excessive heat in the location of the joint with correspondingly higher mechanical and thermal stresses and increased interface oxidation resistance.




## What Is a "Gas Tight" Joint?

There is a certain minimum pressure needed to ensure that the interface of the wire and connector is "gas tight". This means simply that no air containing oxygen can leak into the contact areas that are transmitting both electrical current and heat.

Oxidation of all metals, but especially aluminum, causes a lower conducting film of oxide to be formed which increases resistance "R". Aluminum connectors are mostly tin plated to prevent bare aluminum from oxidizing. If bare aluminum is used, then an anti-oxidant "grease" is often used to prevent oxygen from reacting with the aluminum's surface. The mechanical scraping of the screw under high pressures on the wire when tightening mechanical connectors is generally enough to remove normal oxide on the wires or cable at the points of contact. Tin plating on the aluminum body stops the lug or connector from oxidizing prior to use. Tin is also useful for keeping the aluminum connector body and the copper wires from galvanic activity with each other.

Are Aluminum Connectors Suitable for Wet Locations?

Tin plated aluminum connectors are designed for substantially dry locations, because long term moisture on multi-metal plating (aluminum plus zinc, copper and tin layers) can create significant galvanic activity. The gas tight joints, if they exclude moisture, are unlikely to be affected in the short term but the appearance and reusability of the connector can be compromised by surface plating corrosion.

Unplated aluminum connectors can be used with bare (unplated) aluminum wire and a special air excluding "grease". The "same metal" interface avoids the multi-metal galvanic phenomenon but care must then be taken to ensure surface oxides are removed before or during the formation of the gas tight joint.

For environments with strong electrolytes exposure (acid ground water, sea water, salt spray, or repeated 100% humidity dew point etc.) all copper and bronze (copper + tin) are unquestionably required.

Fortunately, most industrial and commercial installations are by regulation, required to be in dry, airy enclosures which are very suitable for tin plated aluminum connectors.

Tin Plated, Dual Rated Aluminum Connectors are the favorite North American choice for low cost wire termination of high current wires and cables in copper and aluminum and increasingly the first choice for new connector designs for international use. It's hard to argue with a lower cost, universal connector that covers a wide size range of both copper and aluminum wire and stranding types.

For more information talk to Chas Ridley IHI Connectors cridley@ihiconnectors.com