Investigation into the Design of High-Power Plug-In Shipboard Electrical Connectors

by

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Abstract

High-power electrical connections are an essential component to all electric power systems. Such connections are important to the Navy as it increases the use of electric energy in ships. High power involves both high current and high voltage simultaneously and hence connections require careful design regarding both properties. While classical connections are typically bolted or welded, a plug-in type connection would greatly reduce installation time and enable more rapid reconfigurations or adjustments as loads are added or changed. This thesis presents the constraints surrounding electrical contacts and insulation requirements toward the development of a high-power plug-in type connector for Navy application. State-of-the-art plug-in contacts technology and mechanisms are identified. A comparison and selection process of dissimilar rated electrical contacts is proposed through the development of Figure of Merits. Insulation requirements, especially those surrounding creepage distance, are presented for high-power contacts across a range of voltages. Additional Navy specific insulation requirements are identified and related to the impact on a high-power connector. Constraints on both electrical contact and insulations requirements are considered and then applied to a 0.4 MW (1 kV, 400 amp) connector concept design. It illustrates the feasibility of developing a new Navy high-power connector. The concept design was fabricated using 3D printing to verify mechanical insertion force constraints were satisfied.

Acknowledgments

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1 Introduction/Background

1.1 Motivation

Naval ships increasingly require more electric power for the many new electrically powered offensive and defensive systems. The Zumwalt class destroyer was the Navy's first fully electric ship capable of generating 75 megawatts of electric power [1]. The ship used an integrated power system (IPS), an all-electric architecture in which the prime movers provide electric power to the propulsion plant and traditional electric loads. This eliminated the need for separate propulsion and electric prime movers and improved the survivability of the ship, but magnified the need for a robust electrical distribution system. The next generation Navy destroyer, DDG(X), is also planned to be an IPS ship including a 20% electric power margin [2]. The ships of the future can thus be anticipated to employ 100 megawatts or more electric power. With such a rise in electric power comes the requirement to move that power efficiently over compact and reliable power distribution systems.

The Power Electronics Building Block (PEBB) is an Office of Naval Research (ONR) "broad strategic concept that incorporates progressive integration of power devices, gate drives, and other components into building blocks with defined functionality and interfaces serving multiple applications" [3]. They are "foreseen as a key to major reduction in cost, losses, size and weight of power electronics" [3]. The idea is to use the PEBB in an open plug-and-play architecture to build and upgrade the next generation of shipboard power systems.

The modular integrated power corridor, developed at MIT, uses the PEBB as a cornerstone of the power system architecture. The power corridor is an electric distribution concept that "incorporates in a single entity the distribution, conversion, isolation and storage of main bus power throughout the ship" [4]. The power corridor replaces the classic point-to-point layouts in traditional ship power distribution. A power corridor runs the length of the ship allowing for power to be "available at most any place, tapped as needed, now or in the future, [and] enables a more flexible, reliable structure compatible with modern ship requirements" [5].

Inside the power corridor structure, the PEBB is used as a universal converter that provides conversions at various voltages. The vision is to make "a single common unit" that is of a manageable "size and weight that can be carried through the ship and easily racked out and replaced by the ship's crew while underway" [4]. These modular converters would be placed into cabinets for thermal management and mate via electrical connections to the interface junction box which provides connectivity to the bus cable. The number of PEBB stacks and number of PEBBs in the cabinets would be determined in the design of the power corridor network [6]. As the ship upgrades, more power may be required and additional PEBBs can be added over time. The PEBB concept increases the reliability of the power system. Broken or faulty PEBBs could be replaced at sea with spare PEBBs without any loss to power distribution functionality.

In order to facilitate the vision of the power corridor and PEBB the key characteristic to enable the plug-and-play architecture is to define an electrical and mechanical interface for the PEBBs connection into the stack. A sailor compatible, electrically safe Integrated Power Electronics Building Block (iPEBB) is being developed for the Navy by Virginia Tech. A high-power plug-in connector is needed to fulfill the vision of these many iPEBBs connected in resettable configurations.

Alongside the iPEBB application, a quick-connect/quick-disconnect electrical connector and mechanism would greatly facilitate the vision of the installation of pre-built electric corridor units into ships. Fabricating and testing electrical distribution systems and components would increase the reliability of installed systems. New systems and upgrades could be checked prior to shipboard installation saving time and costly troubleshooting efforts that result from issues found after installation.

High power electric connectors operate at high voltage and high current. Traditional connections are bolted or welded, which involve substantial time and manual effort to achieve. Furthermore, without regular inspections and maintenance bolted units can loosen over time, which can cause higher contact resistance and in some cases fires. Thus, the goal of a plug-in connector is to make a quick, safe, and reliable high power electrical connection.

Traditional high power make and break electrical connectors are often designed with the commercial land-based utility industry or temporary power distribution industries in mind. These connectors are not highly constrained by size or weight and are typically bulky, heavily insulated, and cumbersome to manipulate. Conversely, smaller quick connect electrical connectors for mass production are rated for lower power levels insufficient for shipboard use.

The maritime application of a quick-connect electrical connector is unique. No other systems create such power density as an electric ship within such a confined space. The luxury of combining multiple ports and connectors to reach the required current or using bulky single connectors is not viable. There are no commercially available connectors suitable to the task at hand. Nor are there existing design guidelines to build such connectors. The combination of a high current, high voltage, plug-in connector suitable for the confined spaces and environmental conditions of a ship must therefore be developed. This thesis is intended to lay the foundation for such plug-in connectors by establishing configuration principles, existing constraints, overarching design guidance, and specifics on which design quantities are important for the basis of reliable plug-in connector designs.

1.2 Principles of Electrical Contact Resistance

As Holm describes in his classic textbook, an electrical contact is a "releasable junction between two conductors which is apt to carry electric current" [7]. Two electrically conductive surfaces are pressed together through a normal force which creates contact. Due to the microroughness of apparent smooth materials, only a portion of the apparent contact area actually makes true mechanical contact. Additionally, electrically conductive metals are usually covered with an oxide or other electric insulative layer. Electrical contact only happens when the insulative films are ruptured or displaced at the contacting surface. Thus, in an electrical junction the electrical connection is even smaller than the true mechanical contact area. The areas of electrical conductance, the only conductive path from the anode to cathode, are referred to as a-spots. The flow lines of electric current in the normal area of the conductor are distorted and bundle together through the a-spot to the other conductive material. The constriction of electricity narrowing from the normal area of the material through a-spots create increased resistance called the constriction resistance, R_c, of the interface. The contact resistance is the total constrictive resistance provided by all the a-spots plus any additional film resistance that may be present.

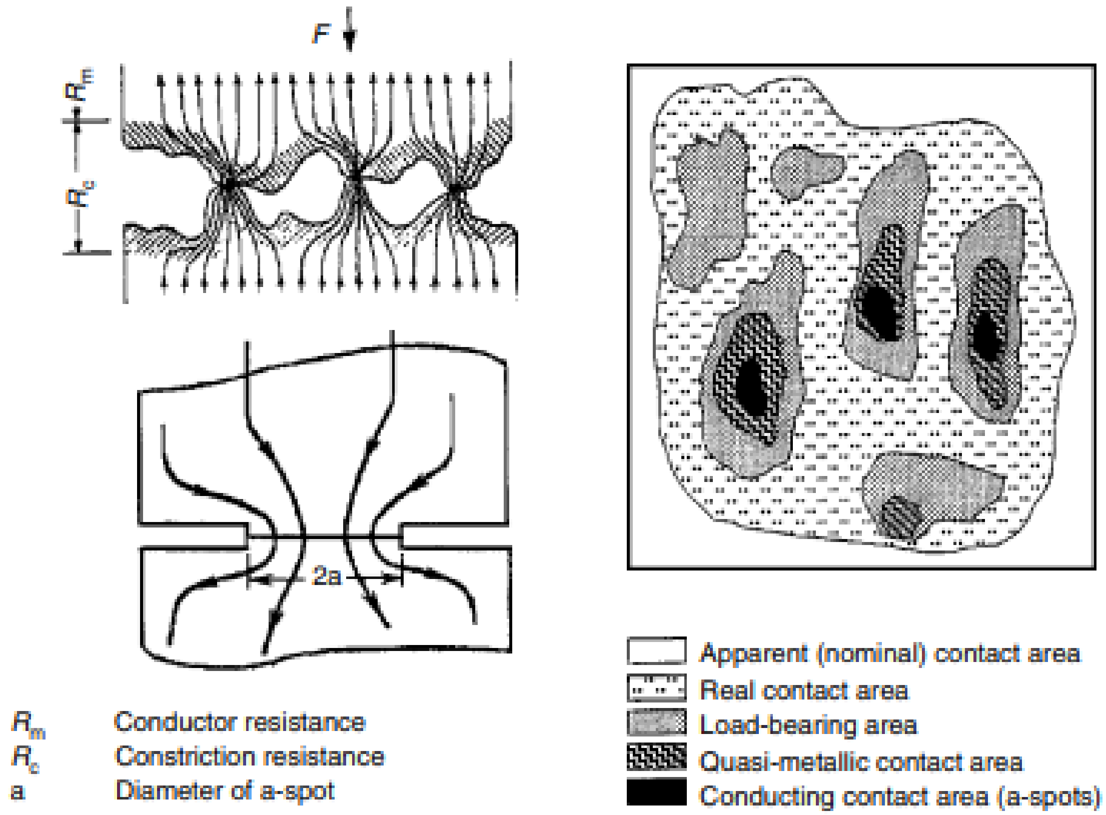


Figure 1-1: Schematic diagram of a bulk electrical interface from *Electrical Contacts* [8]

The higher the normal pressure between the contacts, the greater the plastic deformation and consequently more and larger a-spots. The area of material contact is governed by the equation:

$$F = A_c H \tag{1}$$

where A_c is the area of mechanical contact, F is the normal force and H is the hardness of the metal.

A cluster of a-spots can be simplified to an equivalent single contact area known as a Holm radius (α). Constriction resistance can be approximated using the equation:

$$R_c = \rho/2\alpha \tag{2}$$

where ρ is the resistivity of the conductor. The area of mechanical contact can be approximated as:

$$A_c = \eta\pi\alpha^2 \quad (3)$$

where η is an empirical coefficient of order unity for clean interfaces as defined by Slade [9]. Combining the above expressions leads to the expression of the constriction resistance as:

$$R_c = [(\rho\verb|^|2\,\eta\pi H)/4F]^{1/2} \quad (4)$$

$$R_s = R_c + R_f \quad (5)$$

$$R_t = R_s + 2R_m \quad (6)$$

The total contact resistance of a joint, R_s, is the sum of the constriction resistance and the resistance of any film present, R_f. Thus, it can be seen that the force between the two contacts contributes inversely to a contact's resistance while the contact's hardness contributes directly to the resistance. This is a reason that soft, corrosion resistant metals such as tin, nickel, silver, or gold are often used to cover electrical contacts. The total resistance of contact, from end to end is the sum of the total contact resistance and the conductor bulk resistance, R_m, of the cathode and anode, equation 6, where the cathode and anode bulk resistance are assumed to be equal.

The contact resistance is also affected by the temperature of the metals. As current is constricted and passes through the electrically conductive area, heating of the metal occurs. Holm showed that the contact resistance could be expressed as:

$$R_s(\Theta) = R_s(0)(1 + \tfrac{2}{3}\alpha\Theta) \quad (7)$$

Where $R_s(0)$ is the unheated resistance of the contact joint, α is the normal temperature coefficient of the metal, and Θ is the superheated temperature of the contact [7]. Due to the increase in resistance and heating effects on a metal's mechanical and wear properties, attention needs to be paid to the temperature of the electrical contacts during operation.

Much research has been undertaken to understand the principles of the effects and mechanics of wear, reliability, and heat transfer in electrical contacts. Metal selection of electrical contacts is also a widely studied field. Seven factors have been identified that contribute to creating a good electrical contact: adequate contact force to break through the oxide film, constant contact force over its working life, low contact resistance, constant contact resistance over its working life, good thermal-shock resistance in the event of a short-circuit, creating many large a-spots for a low constriction resistance, and good heat dissipation during continuous operation [10].

There is much less literature and no practical guide on how to combine that information and implement them into a design of an electrical contact complete with a safe and ergonomic insulated housing. Since classical texts and academic papers gave no practical guide on how best to implement the contact normal force in quick connect-disconnectors or how to interface them with an insulated housing, it was decided a thorough search on the state-of-the-art of power connectors was the best way to identify best practices.

2 State of the Art of Electrical Plug-in Connectors

2.1 Commercial Connector Designs

Power connections can be classified into three groups: light-, medium-, and heavy-duty according to Slade [9]. Light-duty connectors are used for devices with currents below 5 A, and voltages up to 250 V. Medium-duty connectors carry currents above 5 A and voltages up to 1000 V. Heavy duty connectors are generally used in utility transmission and distribution systems, carrying high currents, tens of kA, and high voltages, hundreds of kV. The high-power shipboard connector falls just outside for what most medium-duty connectors are designed and rated.

Beyond these three groupings, connector systems are also classified according to their functional operation or how the electrical and mechanical connection is made. These functionality groups as defined by Braunovic et al. are: compression, mechanical, wedge, make and brake (disconnect), and fusion [8]. Compression connectors create a permanent joint through the use of tools "to crimp the connector to the conductor using high force" [8]. Figure 2-1 illustrates an example of a crimp connection.

Figure 2-1: Multiple crimps made on a wire and Phase 3 connector using a hydraulic crimping tool and hexagonal die [11]

Mechanical connections are made through the use of bolts, hardware, or other similar means to create contact between two metals. Examples of mechanical connectors are illustrated in Figure 2-2.

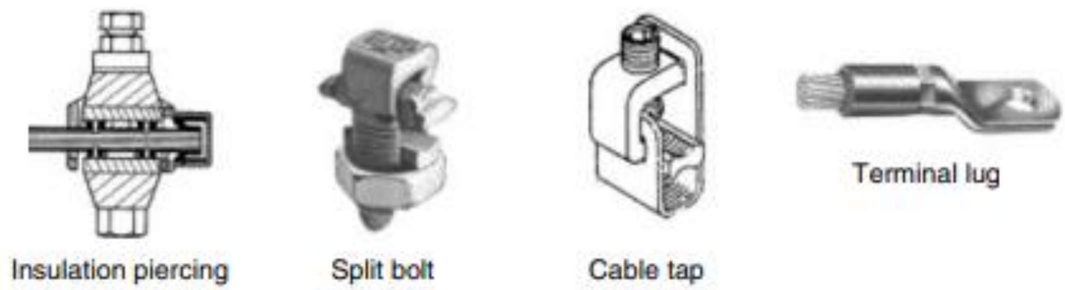


Figure 2-2: Examples of mechanical connections from *Electrical Contacts* [8]

Wedge type connectors use a wedge and C-body to plastically deform two wire conductors. A schematic view of the process is shown in Figure 2-3. Fusion contacts are made through welding, soldering, or brazing.

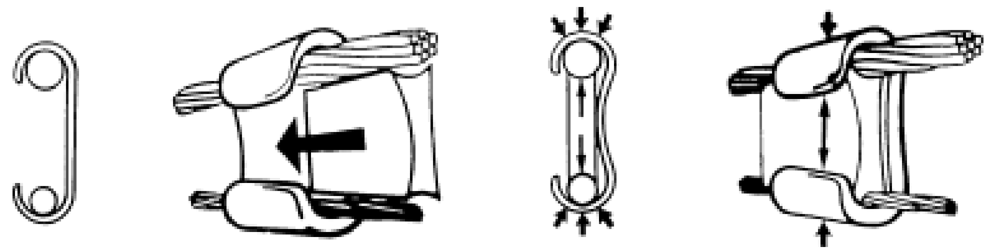


Figure 2-3: Process of mating two wire conductors through a wedge type connector [8]

Finally, make and break contacts, also known as plug-in or plug and socket connectors, use a variety of methods to temporally electrically mate two conductors. Plug and socket connectors are the only type that does not explicitly require tools to mate and are purposely designed to be re-mated on a regular functional basis. This is the type of connection that needed to be investigated for use in the high-power shipboard connector.

In order to identify the characteristics of a plug and socket design for high power application a wide search for commercially available plug and socket connectors was undertaken. The criteria for commercial plug and socket connectors were set at 150 A and 500 V. The current requirement was to ensure that techniques for making forceful reliable contact would be extracted from the commercial review. The voltage requirement was made to reveal insulation techniques and best practices at high potentials for make and break connectors.

The first type of electrical connector that was eliminated by setting a high current rating was the simple pin and socket contact. The most basic plug and socket connector was also one of the most limited. A solid pin sliding against a solid socket with no spring like action elements employed only the initial friction to hold the contact in place and exert a normal force from the pin to the socket. The upper extreme of the simple pin and socket contact were found to be the 150 A military size 0 contact. An example of what a simple solid contact looks like is shown in Figure 2-4.

Figure 2-4: Deutsch solid pin and socket electrical contact [12] [13]

These simple pin and socket contacts were widely used in numerous industries because of their simple design. This design works well in low current applications, less than 150 A, and were available in many sizes. Several of these pin and socket contacts were routinely used in clustered patterns to transmit multiple signals or power phases through a connector. Multiple solid socket contacts could be combined to transmit higher currents, the goal however of the shipboard high-power contact was to use a single pole, that is one contact, for total current transmission. Various configurations with multiple contacts of various sizes are illustrated below.

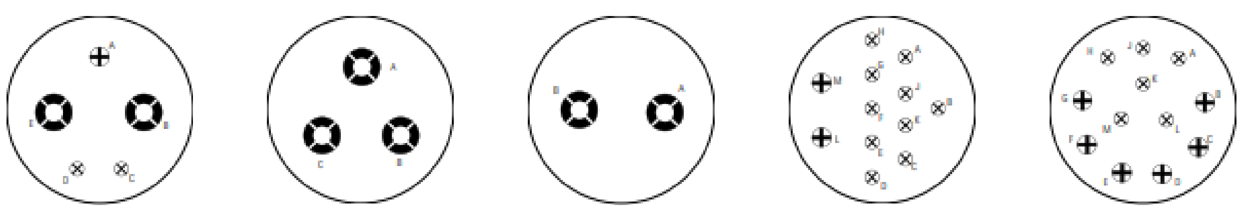


Figure 2-5: MIL-DTL-22992 contact configurations produced by MILNEC [14]

Electrical contacts that created a more robust electrical connection, above 150 A using a single pole, were identified in the commercial search. Over 35 electrical connectors or contacts were investigated ranging across 16 different manufacturers, a list of which can be found in Appendix A. The next step was to classify common characteristics across different connectors to identify the important design principles employed.

2.2 Electrical Contact Mechanisms

This section focuses on mechanisms employed on either the plug (male) or the socket (female, receptacle) that created an electrical contact. Eleven different electrical contact methods were identified in the off the shelf connector commercial search.

2.2.1 Socket Leaf Springs

The most common connection mechanism found in the off the shelf commercial connector review was the use of leaf springs in the socket. These sockets employed a raised “leaf spring” to create a normal force and a-spots on the plug/pin and leaf springs. Figure 2-6 shows the general principle of the socket leaf spring. A cross-sectional view of just one leaf spring is shown and the bold black arrows show the motion of the parts when mated. The plug slides along the leaf spring, removing any oxidized film from both components. Once fully in place, the normal force as a result of the compressed arched leaf spring creates the normal force on the plug.

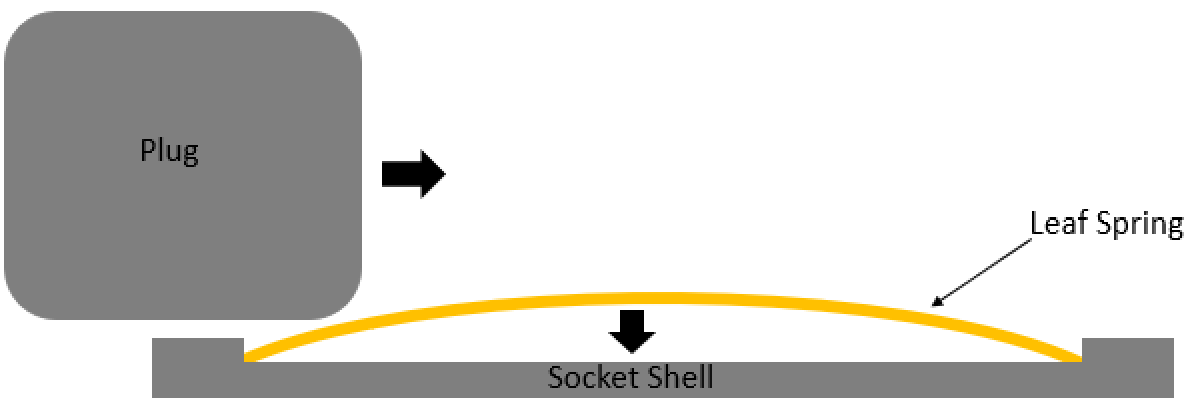


Figure 2-6: Cross section schematic of a leaf spring socket

There have been multiple variations on the basic principle developed by several manufacturers. The width of the leaf spring varied considerably across varieties, for example ODU had two socket leaf spring technologies, one called Lamtac, Figure 2-7, and another called Springtac, Figure 2-8. Lamtac used fewer thicker leaf springs they called “lamella” while Springtac used many wires to act as leaf springs. Throughout all different types of variations, the pin was simply a solid contact.

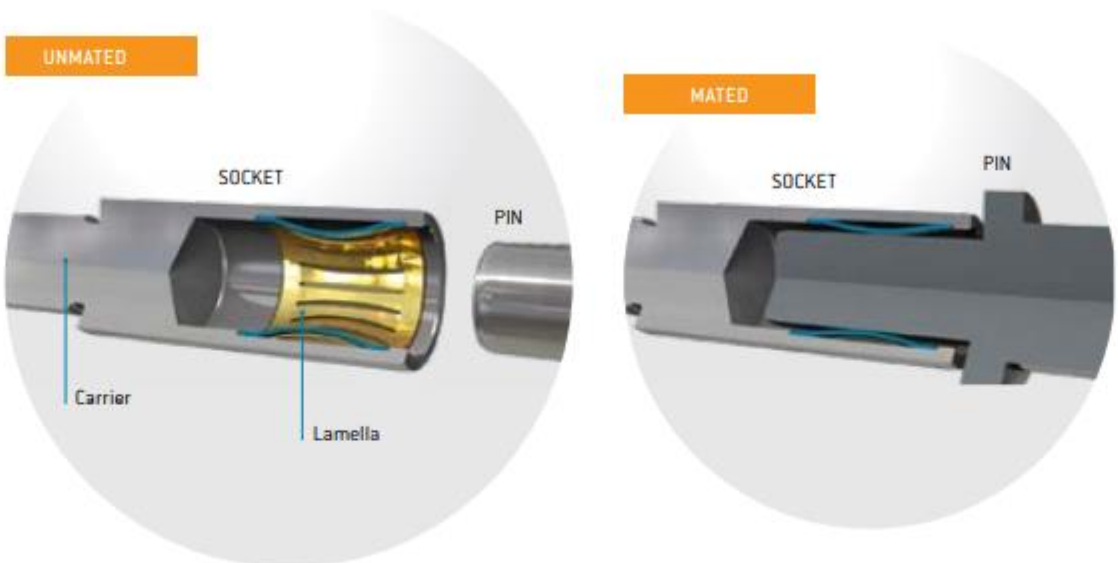


Figure 2-7: Cross section view of the Lamtac contact series offered by ODU [15]

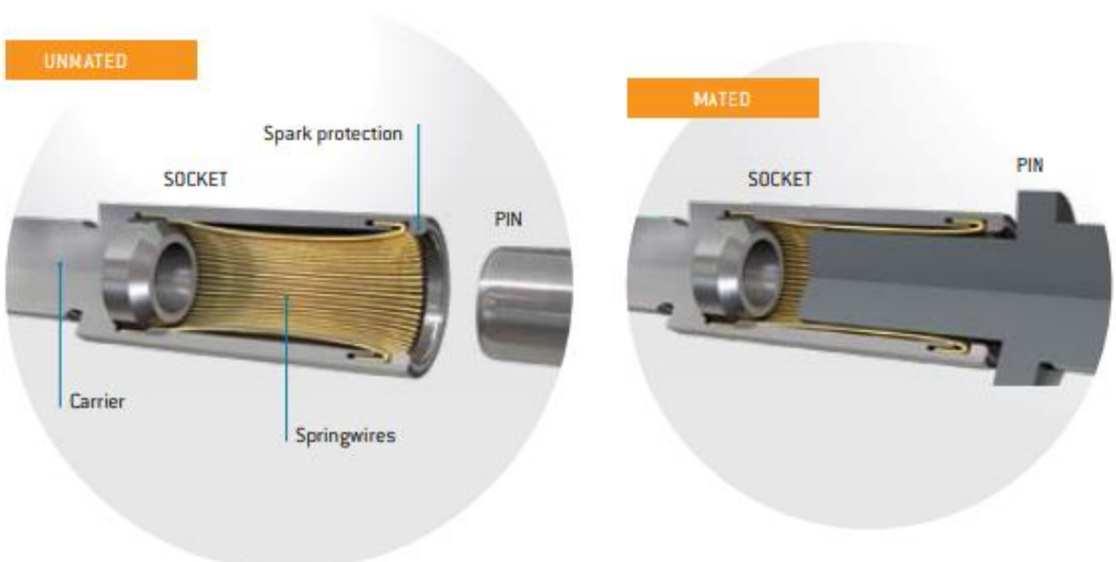


Figure 2-8:Cross section view of the Springtac contact series offered by ODU [15]

Figure 2-9,Figure 2-10, andFigure 2-11 show some pictures of various connectors that employed the socket leaf spring mechanism. The geometry and material selection by the manufacturer were the parameters that set each contact apart from the other.

Figure 2-9: Close up of the ODU Lamtac technology employed in a plug [15]

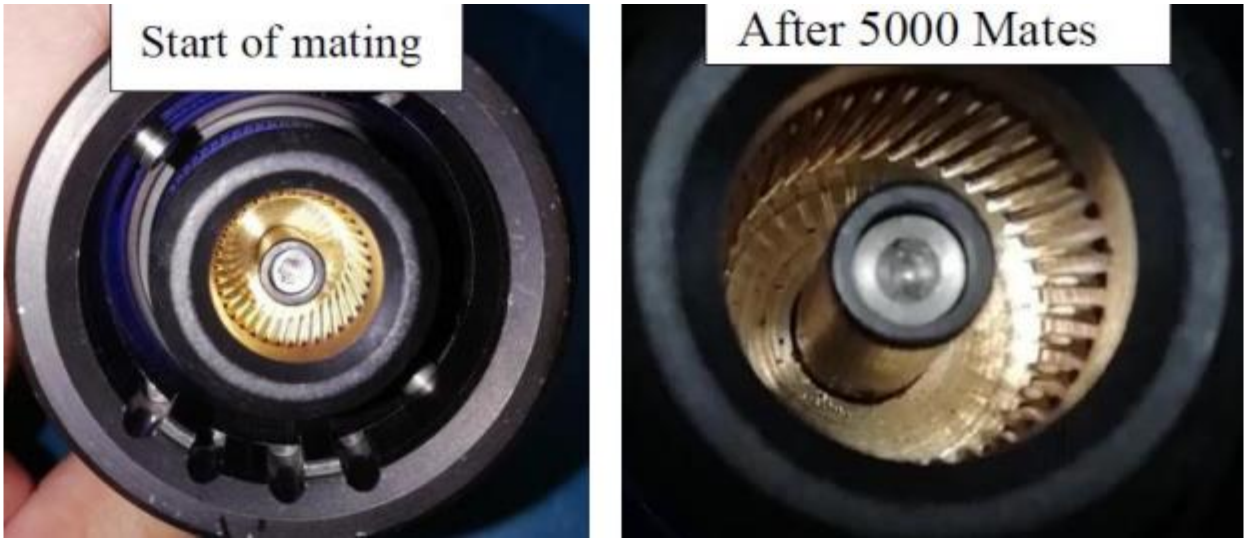


Figure 2-10: The HBB connector developed by Smiths Interconnect [16]

Figure 2-11: A closeup of the leaf springs in the HAN S connector by Harting

A subcategory of the leaf spring mechanism was skewing the leaf springs into a hyperboloid. Amphenol and Smiths Interconnect both employed this technology to make contact with the pin and socket in multiple spots along the leaf spring. Figure 2-12 shows a 3D rendering of the concept and Figure 2-13 shows it applied in a contact.

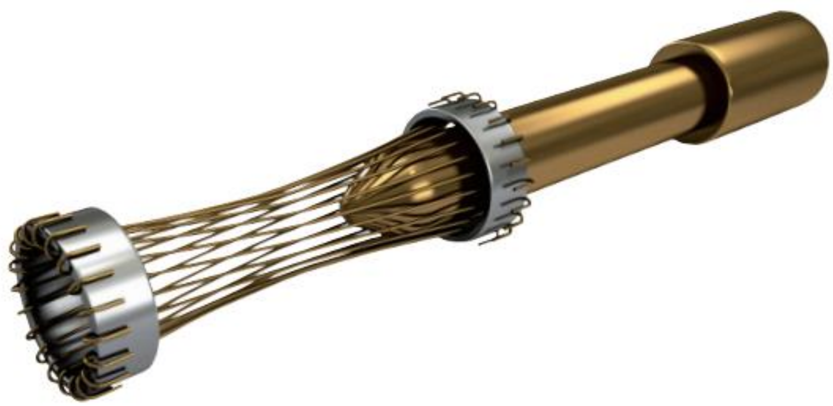


Figure 2-12: Rendering of the hyperboloid principal employed by Smiths Interconnect [17]

Figure 2-13: The hyperboloid technique called Radsok by Amphenol employed on the Radlok [18]

2.2.2 Socket Torsion Louvers

Louvers in the context of electrical contacts, are multiple horizontal conducting elements that contact the bulk male and female conductor to transfer electricity across the gap. The individual leaf springs or lamella introduced in 2.2.1 can also be identified as louvers. In the case of socket torsion louvers, the sockets were lined with individual louvers that deflected under torsion when the plug was inserted. Once again, the plug was a solid pin contact. Similar to the leaf spring concept, each louver formed an independent parallel path from the anode to the cathode. There were found to be two types of torsion louvers, one component and two component louvers. The electrical connector company: Stäubli, had the most variety of torsion louver contacts.

One component torsion louvers were made of one material which provided the electrical conduction path and the mechanical spring force for the connection. The louvers were made in a separate strip, then held in place on a contact (the socket in this case) either through self-imposed pressure when fitted in a socket or through a retention ring. When the pin contact was inserted, the louvers would rotate slightly which created the torsion force which in turn created the normal force on both contacts thus creating an electrical path. Once the initial torsion was created, the pin would slide over the louver removing oxide film through friction until it was fully seated in the contact. Figure 2-14 shows only the louvers without any associated contacts, it shows the louver torsional movement where the left half are not compressed. Figure 2-15 shows a schematic of a torsion louver in a mated configuration with contacts present. The red and blue circles indicate the area of contact between the louver and conductors. Figure 2-16 shows the mating process with a torsion louver contact. The red circle indicates the permanently mounted contact side.

Figure 2-14: Two-component torsion louvers, half in compression [10]

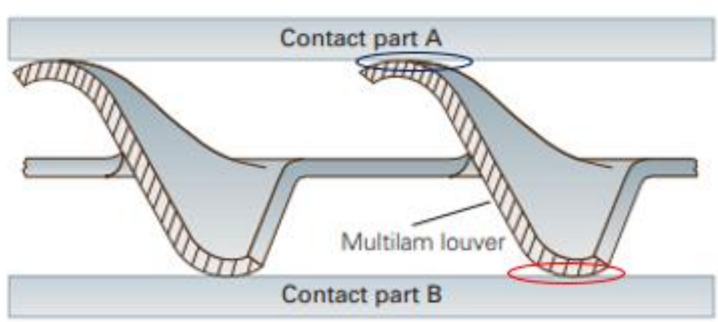


Figure 2-15: A cross section schematic of the one component torsion louver principal in a Multilam contact developed by Stäubli [10]

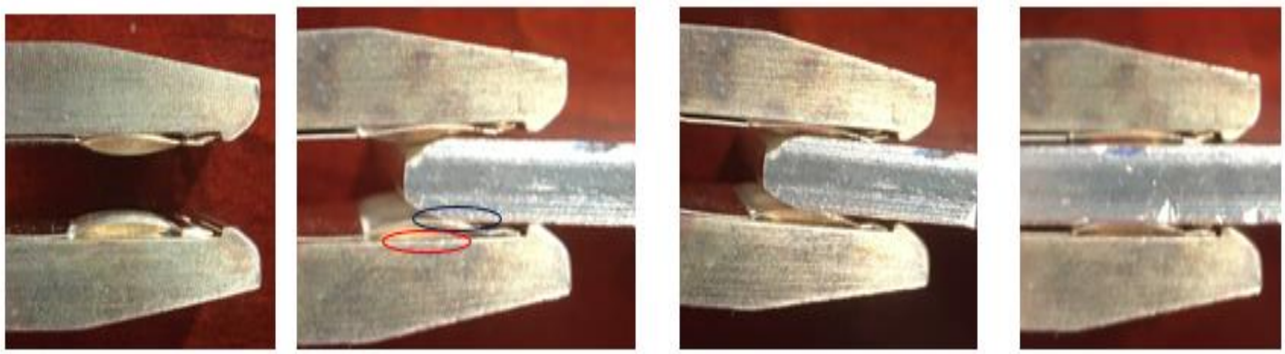


Figure 2-16: The torsion louver mating sequence

A two-component torsion louver was made of two materials, one which provided the electrical path from conductor A to conductor B, and a second material which provided the torsion component of the louver, illustrated in Figure 2-17. Using two separate materials allowed for a broader range of metals in the design. More conductive metals that had poorer elastic properties could be employed as the principal conductor. Separate metals could be chosen that provided the torsion and normal force element without worrying about their conductive properties. This allowed for more consistent force over the lifetime of the louver. It also permitted greater bending of the louver because of the improved elastic properties of the metal. More room for movement consequently improved alignment tolerances. The two component louvers were more complex and were larger than the simpler single component torsion louver. They generally had a greater minimum diameter of the socket they fit into because of the more limited bending radius. The Han S contact was an example of one of the connectors found that employed one component torsion socket louvers, Figure 2-19.

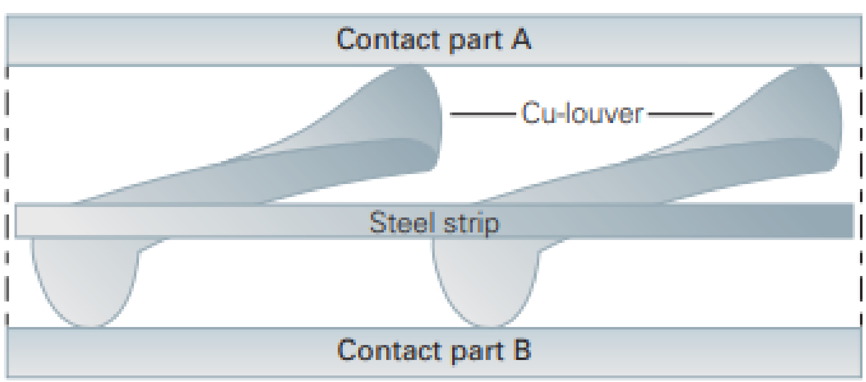


Figure 2-17: A schematic of the two-component torsion louver [10]

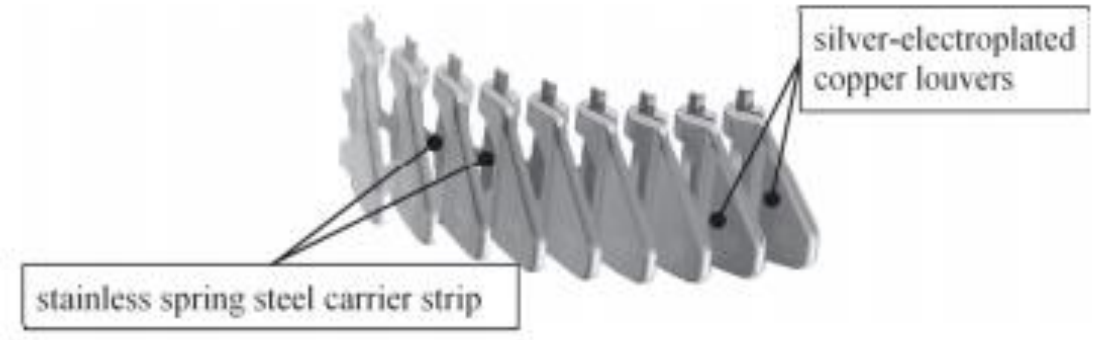


Figure 2-18: A two-component torsion louver band as dipicted in Gatzsche et al. [19]

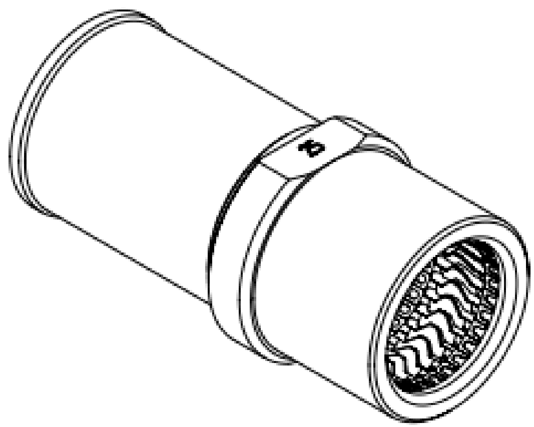


Figure 2-19: The Han S socket with torsion louvers [20]

2.2.3 Plug Torsion Louvers

Similar to socket torsion louvers, plug torsion louvers used the same torsion louver mechanism on the male plug part of the electrical connector as seen in Figure 2-20. Stäubli’s Multilam louvers in particular were developed so that they could be used on either the plug or socket.

Figure 2-20: The Powersafe plug contact with plug torsion louvers

2.2.4 Socket or Plug double spring-loaded louvers

Another electrical connection method that utilized two separate metals to provide the spring force and electrical path was the double spring-loaded louver. The design developed by Stäubli used a thin steel leaf to act as the spring for two electrical conducting louvers, as seen in Figure 2-21. A multitude of these springs and louvers created the complete contact, Figure 2-22. The double spring-loaded louver technique could be applied to fit into a socket or onto the plug end of an electrical connector. The corresponding contact piece would be a traditional smooth plug or socket.

Figure 2-21: A thin steel leaf provided the spring force on the Stäubli ML-CUX double spring-loaded louvers [21]

Figure 2-22: The Stäubli ML-CUX double spring-loaded louvers on a pin and in a socket [21]

2.2.5 Split Plug (double segment)

A slight modification to the simple smooth plug created the split plug. The simple plug was partly cut in half forming the double segment split plug, as seen in Figure 2-23 . The cantilever prongs created the spring force as they were squeezed into a slightly smaller diameter plug which also created friction to remove oxide film. In some cases, a spring element was inserted into the cut, such as can be seen in Figure 2-24, in order to increase the normal force on the socket in an effort to create more contact area and a-spots.

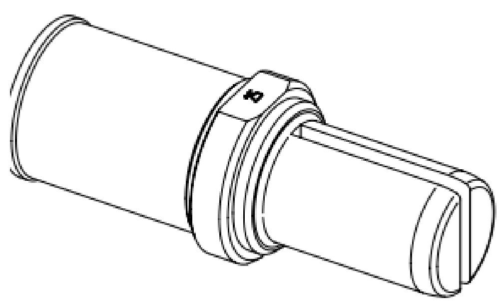


Figure 2-23: An example of a split plug, the HAN TC650 [22]

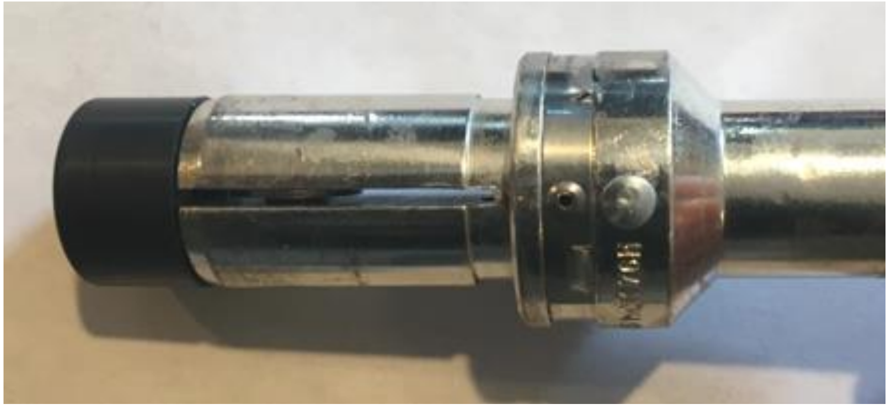


Figure 2-24: A spring element between the two halves of split plug in the Eaton Roughneck contact

2.2.6 Split Plug (Hex segment)

Another modification to the simple plug to make it more efficient was hollowing it out and separating the plug into more segments such as the Kona connector by Harwin, Figure 2-25. The more segments allowed for greater deflection of each cantilever prong and a corresponding increase in normal force. Less force was needed to deflect each prong as they were inserted into the plug compared to a simple plug or split plug being forced into the same reduced diameter socket.

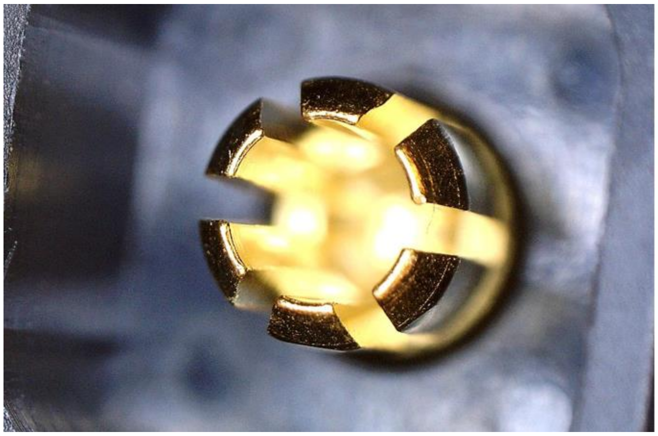


Figure 2-25: The Kona plug by Harwin

2.2.7 Split Socket

The split socket used a similar spring force via cantilever prongs idea except it was employed on the socket side of the electrical contact. All examples of split sockets found were four segment sockets. The socket was sized slightly smaller than the pin and expanded when the pin was inserted creating a normal force between the pin and segment.

Figure 2-26: ODU’s split socket contact called Turntac [15]

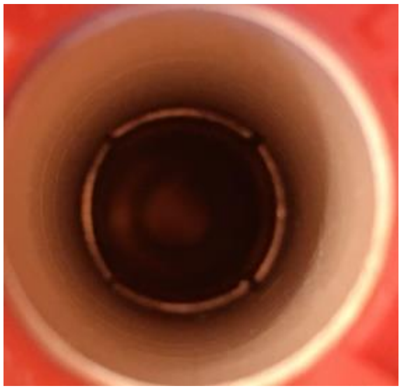


Figure 2-27: A top view of the Hubbell Loadbreak split socket contact

2.2.8 Split Blade Socket

The split blade socket was a common electrical connection method. It was similar to the split socket method, the distinction being the blade socket was shaped in a flat fork shape vice a circular shape. Split blade sockets were found in several varieties, from many prongs surrounding a single blade as in Figure 2-28 , to just a few, Figure 2-29 . This was the same method that was used in the common domestic electric outlet.

Figure 2-28: Split blade socket employed on the Molex EXTreme Guardian Connectors [23]

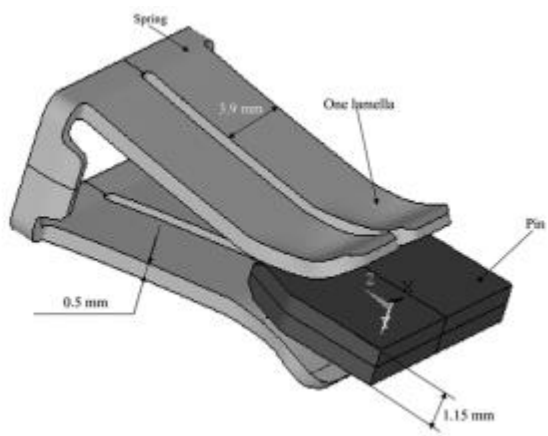


Figure 2-29: The split blade socket was the study of Beloufa et al. [24]

A slight variation off of the split blade socket was the “U Shaped Socket” developed by a group of researchers from Germany for use as a plug-in connector for the Intelligent Stator Cage Drive (ISCAD) Application. Figure 2-30 shows their design. The copper outer U served as the spring component and was inserted around the bar which would be mounted on the stator.

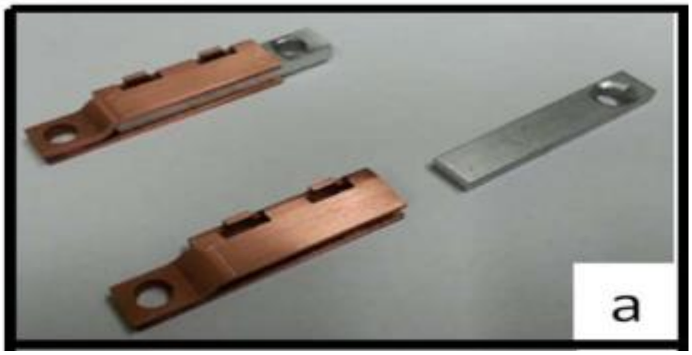


Figure 2-30: A split blade plug developed by Rubey et al. [25]

2.2.9 Floating Contact Compression Spring

A unique design was developed by AZZ Inc. which used a series of solid electrical conductor "fingers" to electrically mate conductors in a circular or linear configuration. The "finger" was in constant linear compression to mate with the stationary conductor and axially compressed when the sliding conductor was inserted. Figure 2-31 shows a finger linearly compressed on the stationary conductor and axially compressed between the sliding and stationary conductors. Figure 2-32 shows a circular configuration of fingers for a connector.

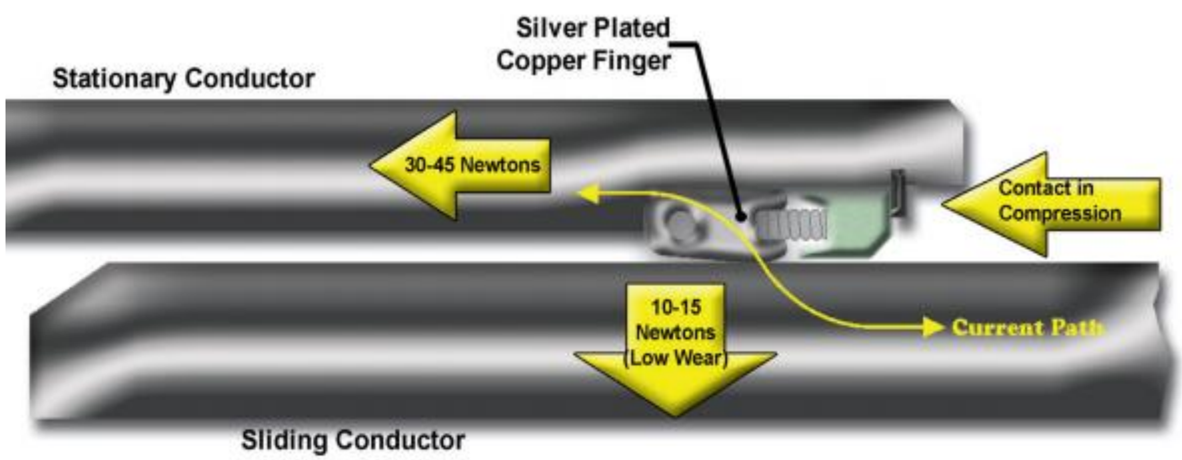


Figure 2-31: Cross section schematic of the AZZ floating contact compression spring mechanism [26]

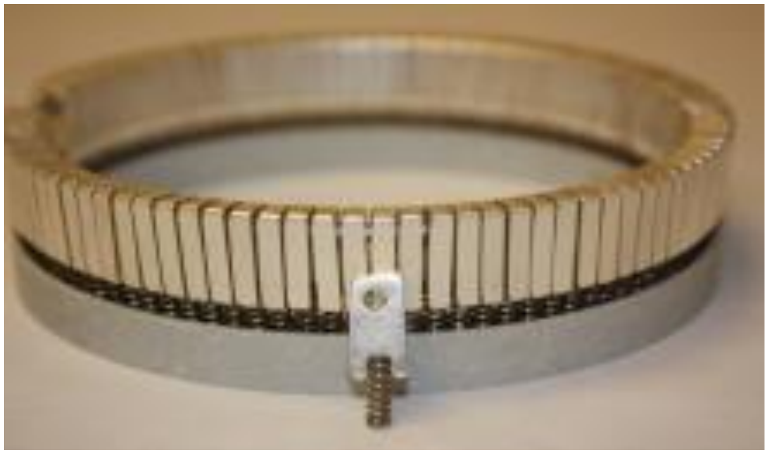


Figure 2-32: A full ring of the AZZ HM contact system [26]

2.2.10 Bus Bar Tensile Coil Spring

A high current bus bar make and break connector was developed by Japan Aviation Electronic Industry (JAE). It was classified as a bus bar tensile coil spring connector since it was developed for use on bus bars, but this technology could be incorporated into a more common make and break electrical connector in the future. One end employed a spilt blade socket connection approach while the other end used a coil spring, teeth, and fabricated holes in the bus bar to make an electrical connection. The mechanism is shown in cross section and in use in Figure 2-33.

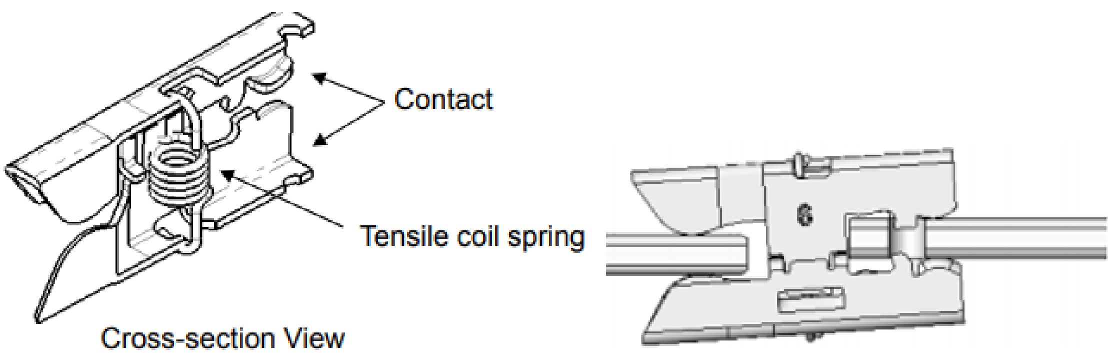


Figure 2-33: JAE DW07 bus bar tensile coil spring contact [27]

2.3 Mechanical Mating Mechanisms

Electrically mating the conductors was the most important aspect of creating a make and break contact, however the electric mating aspect was not expected to hold the connector together. There was an electric mating force associated with electrically creating friction to break the oxide and create a-spots, but there was another force associated with mating the insulation and encasements together which contained the electric contact. This was defined as the mechanical mating force. Together, the mechanical mating force and the electric mating force created a total “connector mating force”, which is what the user feels when they mate full connectors electrically and mechanically. Figure 2-34 illustrates electrically mating the Powersafe contact and Figure 2-35 illustrates the mating of the full Powersafe connector.

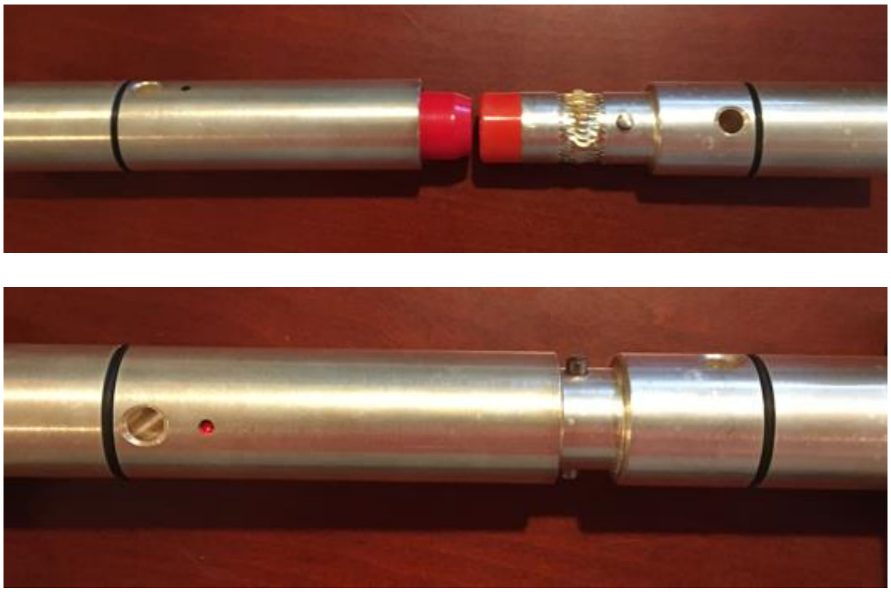


Figure 2-34: Powersafe contact, electric contact mating before and after

Figure 2-35: Powersafe, full connector mating before and after

The electric contact is not designed to hold the connector together. A mechanical mechanism was included as part of the connector insulated case to take the stress and strain around the electric contact. These cases and mechanisms also ensured they would lock together and could not be pulled apart accidently. The off the shelf commercial search identified six common mechanical mating mechanisms employed across all the connectors reviewed to ensure a connector was safely held together.

2.3.1 Bayonet Locking Mechanism

The most common locking mechanism was the bayonet locking system. Employed on cylindrical contact casings, one side was made with radial pins or grooves that fit into matching slots on the other connector. The slots were shaped in a J or L so that the fitting slid along the vertical section of the slot and then rotated horizontally to prevent the pins from being easily pulled out along the vertical section again. Figure 2-36 shows the L shaped groves for the bayonet locking mechanism on the Stäubli 16BL.

Figure 2-36: Stäubli 16BL bayonet locking connector with L shaped slot [28]

2.3.2 Spring-Loaded Clip

The spring-loaded clip came in many forms but the principle was always the same. The connector had a clip with a raised surface that slid into a cutout on the corresponding connector housing which prevented it from sliding out without applying a force to compress the spring. Figure 2-37 shows one such mechanism on the PS3C connector.

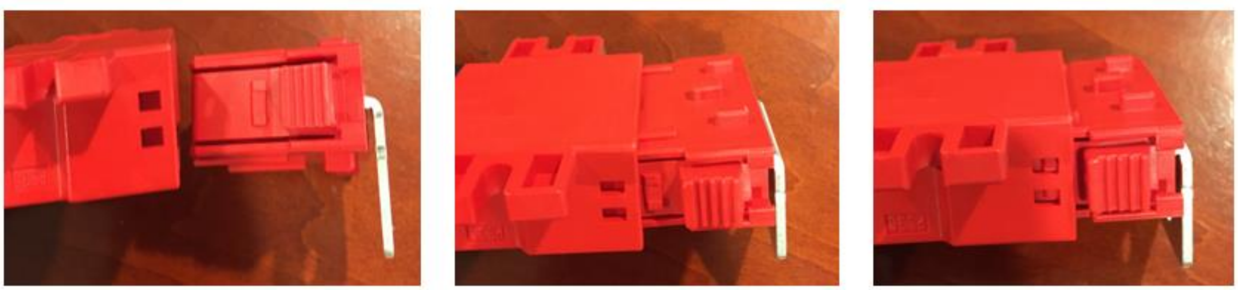


Figure 2-37: The Hirose PS3C connector with a spring-loaded clip

2.3.3 Panel Screws

Some make and break connectors were held together by the more permanent method of screws, thumbscrews, or bolts and nuts. This added complexity to the mating and securing process as it required extra tools and/or time. Figure 2-38 shows a Hirose waterproof connector where the holes for the bolts are circled in red. It also shows a Harwin connector which was held together by thumbscrews.

Figure 2-38: The Hirsoe waterproof connector held together by bolts [29] and Harwin connector with thumbscrews [30]

2.3.4 Screw Ring

The screw ring mating mechanism could be employed on the male or female connector. It was fitted with threads and the corresponding connector was fitted with a threaded cover which screwed down to mate, lock, and weatherproof the connection. Figure 2-39 shows example MILNEC connectors that employed the screw ring mechanism. The left shows the outer screw ring while the right connector shows an inner threaded example.

Figure 2-39: MILNEC connectors with a screw ring connector [14]

2.3.5 Snapping Plate

The Radlok connector used a unique mechanism to lock the connector. It had a snapping plate that fit into a groove on the contact pin. The snapping plate force was generated through an internal spring system in the Radlok. The snapping plate was drawn up for release by pressing a button on the top of the connector. Figure 2-40 displays the elements involved in the design.

Figure 2-40: Radlok snapping plate button and groove in pin [18]

2.3.6 Friction of Shells

Some connectors had no locking mechanism to hold the connector together other than friction between the outer and inner shells of the insulated connector. Figure 2-41 shows the Hubbell Load Break connector which was simply held together by the conical rubberized insulating material. The drawback to the use of friction shells alone was there was nothing locking them in place. With enough force the connector could electrically disconnect inadvertently. It could also add significant mating force because the friction must hold the connector together against the jostling and strain it may undergo.

Figure 2-41: Cross section view of the Hubbell Loadbreak [31]

2.4 Water and Dust Protection Mechanisms

The enclosure aspect of a connector needs to protect the electrical contact from environmental factors such as water, dust, and foreign objects. The ingress protection rating or IP code is an internationally recognized standard developed and published by the International Electrotechnical Commission (IEC). The IEC standard 60529 details the levels of protection an enclosure offers along with the tests the enclosure must pass to rate such protection [32]. The IP code uses a two-digit numerical code to classify the protection provided through an enclosure. The first digit indicates the protection against the ingress of solid foreign objects and access to hazardous parts. The second digit indicates the protection against the ingress of water with harmful effects. Table 2-1 and Table 2-2 display the definitions of each numerical indication as defined by IEC 60529.

Table 2-1: Protection indicated by first characteristic numeral in the IP code

First characteristic numeral	Degree of protection against access to hazardous parts	Degree of protection against solid foreign objects
0	Non-protected	Non-protected
1	Protection against access to hazardous parts with the back of a hand	Protected against solid foreign objects of 50 mm diameter and greater
2	Protection against access to hazardous parts with a finger	Protected against solid foreign objects of 12.5 mm diameter and greater
3	Protection against access to hazardous parts with a tool	Protected against solid foreign objects of 2.5 mm diameter and greater
4	Protection against access to hazardous parts with a wire	Protected against solid foreign objects of 1.0 mm diameter and greater
5	Protection against access to hazardous parts with a wire	Dust-protected
6	Protection against access to hazardous parts with a wire	Dust-tight

Table 2-2: Protection indicated by second characteristic numeral in the IP code

Second characteristic numeral	Degree of protection against water	
	Brief Description	Definition
0	Non-protected	-
1	Protected against vertically falling water drops	Vertically falling drops shall have no harmful effects
2	Protected against vertically falling water drops when enclosure tilted up to 15º	Vertically falling drops shall have no harmful effects when the enclosure is tilted at any angle up to 15º on either side of the vertical
3	Protected against spraying water	Water sprayed at an angle up to 60º on either side of the vertical shall have no harmful effects
4	Protected against splashing water	Water splashed against the enclosure from any direction shall have no harmful effects
5	Protected against water jets	Water projected in jets against the enclosure from any direction shall have no harmful effects
6	Protected against powerful water jets	Water projected in powerful jets against the enclosure from any direction shall have no harmful effects
7	Protected against the effects of temporary immersion in water	Ingress of water in quantities causing harmful effects shall not be possible when the enclosure is temporarily immersed in water under standardized conditions of pressure and time
8	Protected against the effects of continuous immersion in water	Ingress of water in quantities causing harmful effects shall not be possible when the enclosure is continuously immersed in water under conditions which shall be agreed between manufacturer and user but which are more severe than for numeral 7
9	Protected against high pressure and temperature water jets	Water projected at high pressure and high temperature against the enclosure from any direction shall not have harmful effects

The required enclosure protection depends on the environment the connector will operate in. Some outdoor industrial connectors need high dust and water protection (e.g. IP68) while connectors that operate in dry well ventilated space may do well with a lower protection (e.g. IP20). Thirteen of the full connector assemblies reviewed provided an ingress protection rating.

Four water protection mechanisms were identified through the commercial survey: the use of an O-ring or gasket, concentric fitting of soft-on-hard insulating materials, concentric fitting of soft-on-soft insulating materials, and concentric fitting of hard-on-hard insulating materials.

Each method had advantages and drawbacks. The O-ring or gasket method was the most popular, 44% of surveyed connectors employed this technique. It was highly effective as the lowest cited protection was rated at IP65 and the highest at IP68. A drawback to using a gasket was that it presented a single point of failure where a tear or deterioration in the O-ring would result in loss of water protection.

Figure 2-42: O-ring used for weatherproofing on the Powersafe Connector

Using concentric fittings of soft-on-hard materials was the surest way to ensure water protection. All connectors that employed this technique had a rating of IP68. The only connector that was marketed as a water-submersible connector employed this technique. To employ this method, it was necessary to have enough material overlap to ensure a watertight seal between the hard and soft material. The RobiFix connector used this technique. In Figure 2-43 the upper section is a shiny hard plastic which created a seal when the lower softer polymer was inserted in place with an overlap of 28 mm.

Figure 2-43: RobiFix connector, an example of soft-on-hard insulation waterproofing

Concentric fittings of soft-on-soft materials were less effective at keeping water out according to the commercial connector survey and associated IP codes. With the exception of one outlier, all connectors with this technique had a protection of IPX4. In order to keep mating forces low and manageable the soft insulators were given a lower tolerance for fit, meaning they did not press as tightly together which would allow for water penetration under certain circumstances. The exception of this rule came in the form of the utility Loadbreak elbow connector which was rated for IP67. The concentric outside and inside had a very tight-fitting design which created a water tight barrier but resulted in high mating force.

Finally, connectors which were simply mated with protection by hard insulation pressed to other hard insulation and held together by a mechanical mating mechanism resulted in low or no protection from water, such as the Han S. With no material deflecting along the small deviations and ridges of the other hard material, no watertight or resistant seal was created.

3 Electrical Connector Design Process

3.1 Overview of the Design Process

Knowing the common and innovative methods of electrical and mechanical connection was not enough to create a high-power connector. A systematic design process needed to be developed in order to capture all constraints and required parameters early in the design; how to evaluate the design for electrothermal and wear reliability; and how to evaluate the insulation and housing aspect of the design for safety. The electrical connector design process was created based on the framework laid out in the research article "A Systematic Approach for the Reliability Evaluation of Electric Connector" [33]. The new design process created was broken into two phases: the functional design phase and the reliability design phase. The full twelve step process is laid out below:

Functional design phase

1. Define Constraints
    a. Current rating and voltage rating
    b. Define Mechanical Structure Limits: Interface, Mounting, Housing, Termination, Creepage length
    c. Electrical Performance: Dielectric breakdown voltage, Maximum bulk temperature, Allowable power dissipation
    d. Mechanical performance: Limits on terminal insertion and withdrawal forces, Durability, Vibration bandwidth
    e. Environmental Performance: Operating temperature range, Thermal shock, Humidity, Water and dust protection
2. Develop Structure
    a. Define structure of the contact and housing (preliminary physical design)
    b. Structure is dimensioned: Based on space and termination mode
3. Material Selection
    a. Define contact surface plating
    b. Select preliminary substrate conductivity
        i) Select as a starting point for the design
    c. Evaluate the resistance of the contact with plating and substrate
4. Set Parameters of contact voltage drop
    a. Define maximum allowable contact voltage drop
        i) Conduct electrothermal analysis without contact resistance
            (1) If resulting temperature > specification defined earlier: Increase the conductivity of substrate in step 3 and repeat and/or redefine temperature operating range in 1b
            (2) If resulting temperature < specification: continue

ii) At this step, the allowable power dissipation between contact surfaces should be defined (allowable power dissipated through contact resistance turning into heat)

iii) Additionally, keep voltage drop below 20 mV to avoid softening of material

5. Theoretical electrothermal analysis
    a. Find minimum allowable contact resistance
        i) Input: current through contact and voltage drop allowed, output: resistance
        ii) Future contact resistance must be lower than this calculated value
6. Theoretical Contact Analysis
    a. Find the minimum contact force based on the minimum contact resistance and material properties of substrate
        i) Gives the minimum contact force the "spring" must provide
    b. Find the restoring force of "spring" based on the contact force
    c. Find maximum stress in "spring" (input: restoring force, output: max stress)
    d. Find the minimum yield strength of the material (input: max stress, output: yield strength)
        i) Determine substrate material
        ii) Determine upper limit of contact force based on geometry and yield strength of selected material
    e. Conduct electrothermal analysis with contact resistance

Reliability design phase

7. Identify degradation mechanisms
    a. Substrate degradation
        i) Stress relaxation evaluation: Determine the maximum allowable relaxation percentage (based on maximum allowable contact resistance which also determines minimum contact force and temperature range)
        ii) Thermal diffusion evaluation: determine its effects on contact resistance
    b. Surface degradation analysis
        i) Sliding wear evaluation: determine the number of mating cycles for the connector
        ii) Fretting wear evaluation
            (1) Determine the upper limit of contact force based on an increase in resistance due to wear during vibration
    c. Surface and substrate compatibility
        i) Thermal expansion
        ii) Intermetallic
9. Vibration reliability analysis
    a. Determine minimum contact force is satisfied for vibration and impact scenarios
10. Anti-overcurrent ability is assessed
11. Evaluate connector housing impact
12. Evaluate housing safety

3.2 Functional design phase

The functional design phase was comprised of defining the initial constraints and parameters, developing an initial design and then evaluating and redesigning as necessary to create a connector that performs under the required conditions.

3.2.1 Define Constraints

The first aspect of the design process was to define the constraints on the connector. These came in four categories: electrical performance, mechanical structure limits, mechanical performance and environmental performance. Defining the current and voltage, step 1a, was separated from the other electrical performance characteristics because this was the starting point for the high-power shipboard connector. Other electrical performance constraints were defined such as acceptable power dissipation by the contact and by the total connector, and dielectric breakdown voltage of the insulation.

Mechanical performance constraints such as the maximum force to insert and mate the connector were defined. The mechanical structure parameters defined included the maximum dimensions of the contact and housing as well as the required creepage distance based in the voltage characteristic. How the contacts would terminate or the type of connector housing that would be used were also important parameters. Finally, environmental performance was defined based on the ambient conditions in which the contact would operate.

Ambient temperature was a very important constraint that fell under environmental performance. Higher ambient temperatures led to hotter contacts; hotter contacts had lower current capacity compared to the same contacts at lower temperatures. The current capacity of a contact was limited by its thermal properties which was a function of the ambient temperature and the self-heating aspect of the metal carrying the current. If possible, it was beneficial to the design process to define the maximum bulk temperature of the contact and maximum temperature of the contact's material.

Constraints came from the electrical and physical requirements imposed on the connector and the designed operating conditions. Constraints and requirements may have been explicitly stated by the user or implicitly based on safety standards and similar connector characteristics.

3.2.2 Develop Structure

Once all the constraints were defined a preliminary physical design of both the contact and housing were made. The type of electrical connection method was chosen and the arrangement of the method was decided upon based on the allowable space and termination modes of the connector. Initial dimensioning of the insulation was made based on the housing safety and protection requirements of the connector. The use of computer-based library of past connector designs could be useful to inform new designs as suggested by Yap [34]. Reviewing high-power commercial connectors and underwater connector designs, such as papers by Galford [35] and Remouit [36], could inspire waterproofing methods and physical structure of connector designs. Other sources of structural inspiration could include automotive electric drive power connectors used in the electric vehicle industry [37] [38], a high current connector made for pulsed electric weapons [39], or the underground dead break utility sector [40].

3.2.3 Material Selection

Initial selection of the insulation materials based on the defined structure and constraints was made. The contact's surface plating was selected taking into account the properties of the coating as suggested by Yasuoka et al. [41]. Initially only substrate conductivity was defined. Total resistance of the contact plating and substrate was theoretically computed.

3.2.4 Set Parameters of contact voltage drop

The maximum allowable contact voltage drop at the contact point was defined using the allowable power dissipation constraint. Theoretically calculating the voltage drop using Finite Element Modeling (FEM) is the best practice for this step. Many papers demonstrate how well FEM programs can handle the electrothermal analysis required to accurately compute the voltage drop through a contact [42] [43] [24] [44].

First the electrothermal analysis was conducted assuming the contacts were one solid piece using just the bulk resistance. If the resulting temperature rise in the contact was higher than the specified temperature defined earlier, the conductivity of the substrate from step 3 was increased. Once the temperature was below the specified temperature the process proceeded knowing the voltage drop through the bulk material. The voltage drop across the contact point and allowable power dissipation through contact resistance turning into heat were identified. The voltage drop across the contacts generally needed to be lower than 20 mV in order to avoid softening of the metal [9] [45].

3.2.5 Theoretical electrothermal analysis

In this step the minimum allowable contact resistance was identified using the current through the contact and allowable voltage drop identified in step four [33] [44]. In future steps, the contact resistance needed to be lower than this calculated value.

3.2.6 Complete electrothermal analysis with contact resistance

Using the minimum contact resistance, the minimum contact force that needed to be exerted was calculated [33] [42] [44] [46] [47] [48] [49] [50]. This provided the minimum normal force the "spring" had to provide. From there the restoring force of the "spring" and maximum stress in the "spring" were identified. Using the maximum stress as an input the minimum yield strength of the material was determined [24] [50]. Based off the found material properties and identified electrical properties of the substrate from earlier, the substrate material was chosen [51] [52].

At that point the substrate and coating were selected. The upper limit of the contact force was determined in order to lower the contact resistance as much as possible. Finally, a full electrothermal analysis was conducted with the chosen materials and forces to confirm the contact was within the defined constraints [42] [19] [25].

3.3 Reliability design phase

The next phase of the design process was to assess contact design and preliminary housing design for the intended environment, application, and lifespan.

3.3.1 Identify degradation mechanisms

Depending on the metals chosen there were different degradation mechanisms at work. Surface film formation was a common mechanism as was fretting corrosion and creep. If degradation mechanisms were identified they could be specifically tested and defended against. A substrate degradation method that was always considered and evaluated was stress relaxation. As the connector was used, the metal would undergo stress relaxation and would not exert the same force as it did when first manufactured [33] [42] [53].

Thermal diffusion occurred when the substrate diffused to the surface of the coating which increased the resistance of the contact. Different combinations of metals and thicknesses affected the rate of diffusion [54]. This phenomenon should be evaluated to determine the effect on the contact over its expected lifespan [55].

Surface sliding wear evaluation determined the number of mating cycles the contact could undergo before needing replacement [56]. This was especially important if mating cycles was a defined constraint. Fretting wear was evaluated for its impact on resistance as a result of vibration and mating [57] [58]. The compatibility of the surface coating and the substrate were evaluated for differential thermal expansion coefficients so as one metal did not unduly stress the other upon heating. Finally, intermetallic formation at the interface between the two metals as a result of current surges in the electrical signal needed to be assessed as the formation could raise the resistance and lower the mechanical strength of the contact over time [59].

3.3.2 Vibration reliability analysis

Depending on the application, vibration analysis was conducted on the contact and housing to ensure proper forces were applied in order to keep the connector and contact intact without disturbance in the electrical connection [43] [60] [61].

3.3.4 Assess Anti-overcurrent ability

The ability to withstand higher current pulses for varying amounts of times was investigated in order to asses if and how much overcurrent protection was needed in a circuit using the contact [33] [47].

3.3.5 Enclosure review

The impact of the connector housing that encompasses the contact had on the contacts performance was evaluated. It was determined if the housing adversely impacted the temperature of the contact or if there were additional limitations that needed to be applied to the structure. The connector enclosure was redesigned as necessary.

3.3.6 Evaluate housing safety

Beyond the impact of the enclosure on the contact, the enclosure needed to be assessed for safety to the personnel handling the connector. Creepage requirements needed to be long enough for the anticipated environmental conditions [62] [63] [64].

The result of following the twelve-step design process was an electrical contact that was designed to meet the constraints of the application. If at any stage of the design process the connector failed the evaluation of a step, the designer needed to revert to an earlier step in the process to correct the short comings and follow the proceeding steps again.

Having defined a process for connector development and testing, work turned to creating a method to evaluate existing electrical contacts. By being able to quantitively identify well performing existing market contacts that had been through a commercial manufacturers functional design phase, the design of the high-power contact could be accelerated by incorporating an existing contact into the connector design. If existing contacts did not meet specifications precisely, they could be used as a starting structure in the functional design phase. Much of the wear and metallurgical issues had already been investigated and addressed in the manufactures' development of existing contacts.

4 Louver Based Electrical Contacts

The common theme across all of the off the shelf commercial connector electrical mating mechanisms reviewed was the use of multiple mechanically independent, low resistance contact points. Chapter 2 described all categories of electrical mating mechanisms found during the connector review. Seventy-three percent of the connectors used multiple individual spring-loaded contact points in order to achieve electrical connection between the bulk plug and bulk socket contacts. The technique to provide separate local area contact points each with individual spring like properties, thus ensuring constant local area pressure, was referred to as a “louver” contact. Louver was the general term used to categorize these metal-to-metal contacts where one side used individual spring like “fingers” while the corresponding contact side was a flat surface. Chapter 2 broke the general classification of louver into a number of categories including leaf springs, torsion louvers, floating contact compression spring mechanisms, and double spring-loaded louvers. Figure 4-1 illustrates the concept of multiple louvers and shows the electric equivalent circuit of one louver. The advantage of the louver was that many of these equivalent circuits act in parallel, reducing the total resistance. Each louver had its own independent spring pressure to ensure the multiple parallel paths stayed in contact with adequate pressure. Even if one failed it would not affect the other spring mechanisms and many electrical paths would still exist.

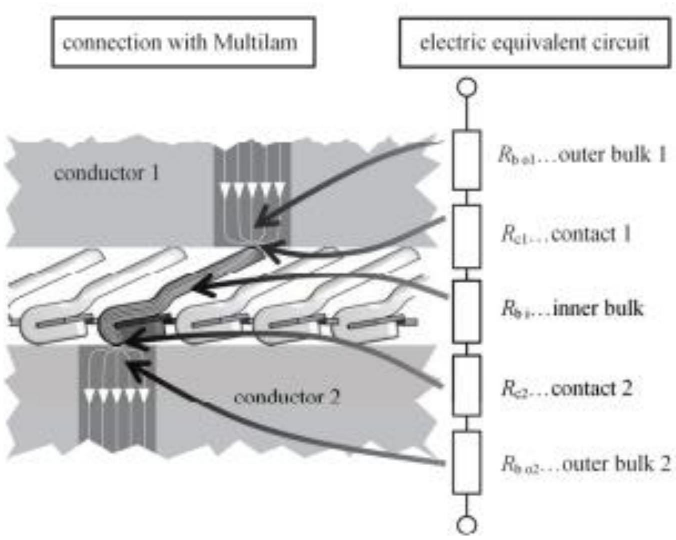


Figure 4-1: Diagram of the electric flow lines through a torsion louver from Gatzsche et al. [19]

4.1 Multilam

A particular diverse brand of torsion louvers was called Multilam produced by Stäubli. These torsion louvers were produced in strips and could be inserted into sockets or attached on the outside of a plug. When deciding to use Multilam in a plug vs. socket configuration there were a couple of considerations to keep in mind. The louvers were better protected in a socket configuration. If it was installed on the plug and the plug was dropped or not handled properly, there was a higher risk that the louvers would be damaged. Secondly, in a plug configuration, the louver strips would require something to retain it in place, for example a groove with an undercut or snap rings as shown in Figure 4-2.This could increase manufacturing/material costs. In a socket configuration, some Multilam were self-retaining in the groove as shown in Figure 4-3.

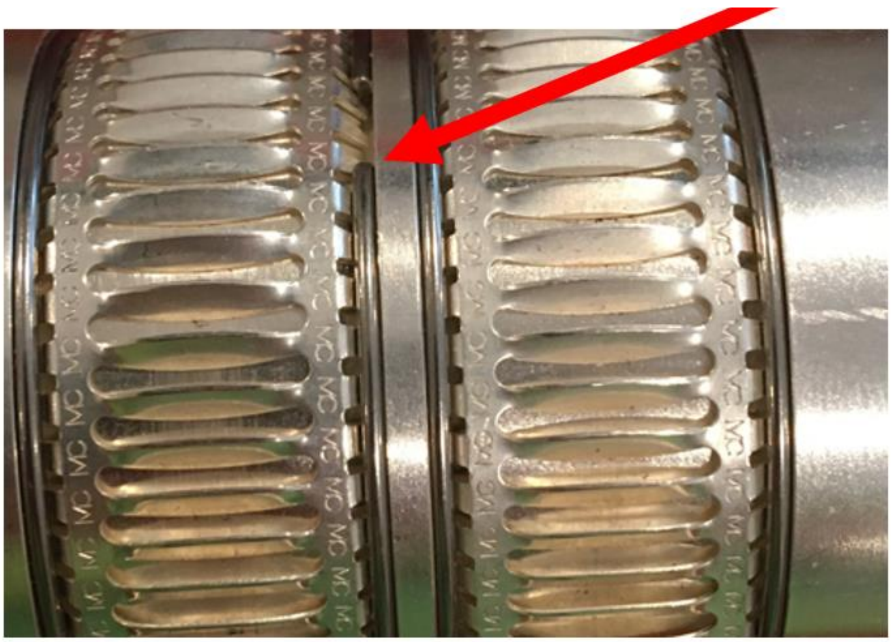


Figure 4-2: A BL25A contact with the Multilam on the outside with retaining rings to keep it in place.

Figure 4-3: Self retaining Multilam in a socket

As discussed in Chapter 2, torsion louvers came in one component, type I, and two component, type II, configurations. Multilams were offered in nine different variations, five type I, as shown in Figure 4-4, and four type II, as shown in Figure 4-5. Each variation offered a different geometry and louver spacing which affected its current capacity, normal force, contact resistance, minimum bending diameter, and maximum bending diameter. Minimum bending diameter was defined as the diameter of the tightest circumference the strip of Multilam could be bent into for application on a plug or in a socket. Figure 4-6 shows the array of different types of Multilams available and their comparative sizes. Each type of Multilam was offered in varying strip thickness which affected the five properties stated earlier. Generally, a strip with thinner Multilams were used for high mating frequency applications and thicker strips were used in less frequent mating applications.

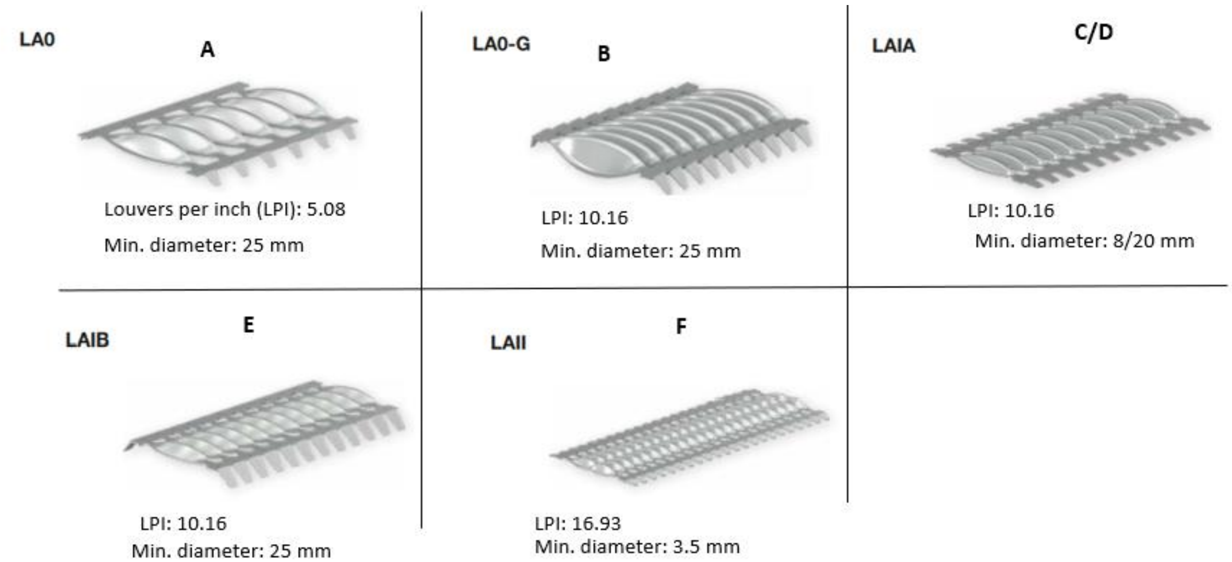


Figure 4-4: Type I Multilam louvers

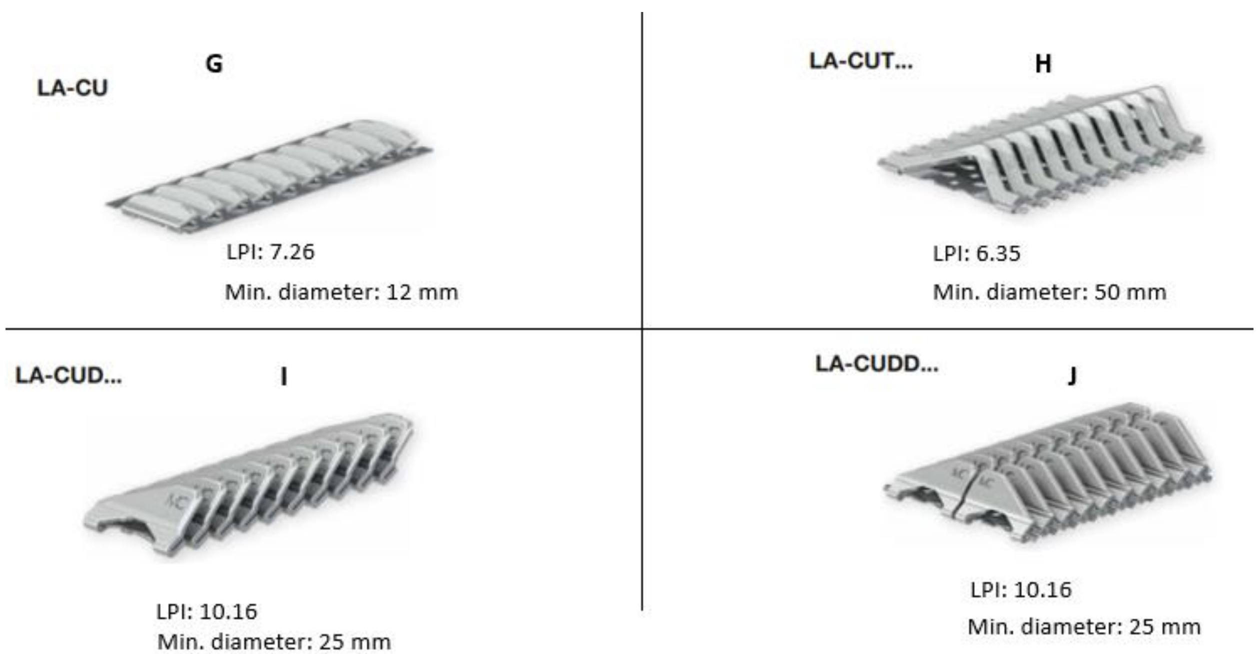


Figure 4-5: Type II Multilam louvers

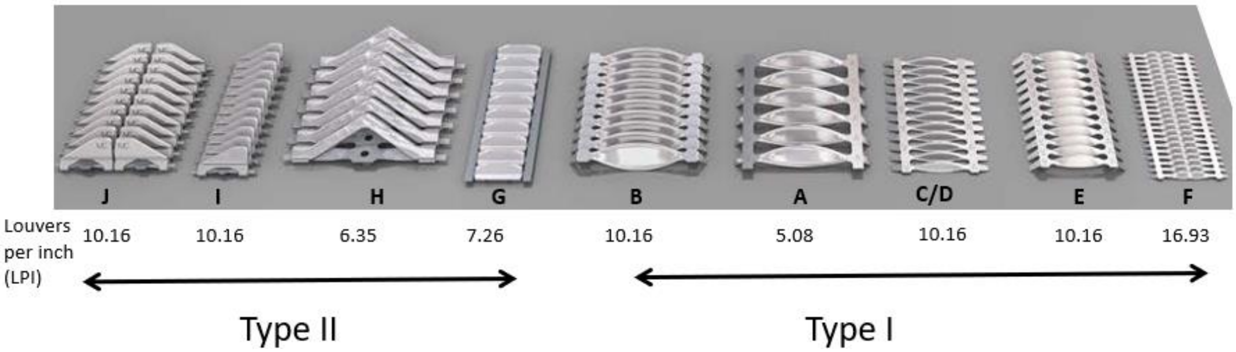


Figure 4-6: Side by side size comparsion of different Multilam variations offered by Stäubli [10]

4.2 Methodology for Multilam design

A methodology to design a Multilam contact was developed with equations presented by Stäubli [10]. The methodology was based on designing the smallest diameter contact, based on physical space, given a specific louver and extracting the characteristics of resistance, current capacity, power attenuation, and sliding force.

n=number of louvers
d=diameter of contact
r=contact spacing
R_I=Overall resistance of whole contact assembly
R_{st}=Average contact resistance of one individual louver
F_s=Sliding force of a contact
μ_r=Friction coefficient
F_k=Contact force per louver
I_w=Rated current of whole contact assembly
I_p=Rated current for one individual louver

$$n = \frac{d * \pi}{r} \tag{1}$$

$$R_I = \frac{R_{st}}{n} \tag{2}$$

$$I_w = n * I_p \tag{3}$$

$$P = {I_w}^2 * R_I \tag{4}$$

$$F_s = n * \mu_r * F_k \tag{5}$$

First the given diameter was used in equation (1) to find the number of louvers that would fit and rounded down to the nearest whole number. The overall contact resistance and total current capacity were found based off the number of louvers using equation (2) and (3) respectively.

Power dissipation was based on the current capacity and resistance of the contact assembly. Finally, the sliding force was found by means of equation (5), using a friction coefficient and the normal force exerted by the louvers. Throughout this paper a standard friction coefficient of 0.35 was used in all calculations. It is important to note that the friction coefficient can be affected by surface treatments, lubricants, and base material of the contact part. All electrical information presented for Multilam was based on optimum conditions: surfaces had clean coatings, not oxidized or polluted and the ambient temperature was 20°C.

Table 4-1: Multilam variant characteristics and minimum diameter design characteristics

	A	B	C	D	E	F	G	H	I	J
	LA0/0.30	LA0-G/0.25	LAIA/0.25	LAIA/0.50	LAIB/0.30	LAII/0.20	LA-CU/0.15-0.5	LA-CUT/0.25	LA-CUD/0.15	LA-CUDD/0.15/0
Louvers per inch	5.08	10.16	10.16	10.16	10.16	16.93	7.26	6.35	10.16	10.16
Louver pitch (spacing) (mm)	5	2.5	2.5	2.5	2.5	1.5	3.5	4	2.5	2.5
Resistance of one louver (ohm)	0.00029	0.0003	0.00035	0.00025	0.0003	0.00035	0.0003	0.0004	0.00033	0.00014
Rated current of one louver (A)	43	38	29	43	35	23	40	40	50	90
Contact force per louver (N)	17	9	20	105	32.5	16	7	10	5	10
Minimum diameter (mm)	25	25	8	20	25	3.5	12	50	25	25
Design based on minimum diameter										
Round Contact: diameter (mm)	25	25	8	20	25	3.5	12	50	25	25
# of louvers	15	31	10	25	31	7	10	39	31	31
Resistance of contact (μΩ)	19.33	9.68	35.00	10.00	9.68	50.00	30.00	10.26	10.65	4.52
Current Capacity of contact (A)	645	1178	290	1075	1085	161	400	1560	1550	2790
Power dissipation (W)	8.04	13.43	2.94	11.56	11.39	1.30	4.80	24.96	25.58	35.15
Sliding force of contact (N)	89.25	97.65	70.00	918.75	352.63	39.20	24.50	136.50	54.25	108.50

The top half of Table 4-1 shows the governing parameters for the selected Multilam variants. The bottom half of the table shows the characteristics of each Multilam variant at its minimum diameter. The same equations could be used to design a Multilam using total contact current capacity as a starting point in order to determine the number of louvers necessary and corresponding diameter, resistance, current capacity, power dissipation and force.

Due to the minimum diameter constraint on the Multilams, some were restricted on how they could optimally be designed for space savings for current ratings under their minimum diameter current capacity. Table 4-2 displays an attempt to design contacts around a current capacity of 400 A. Only Multilams C, F and G could be improved to have less louvers and a smaller diameter than the required minimum diameter.

Table 4-2: Multilam design for a 400 A current contact

	A	B	C	D	E	F	G	H	I	J
	LA0/0.30	LA0-G/0.25	LAIA/0.25	LAIA/0.50	LAIB/0.30	LAII/0.20	LA-CU/0.15-0.5	LA-CUT/0.25	LA-CUD/0.15	LA-CUDD/0.15/0
Design based 400 A										
Round Contact: diameter (mm)	25	25	12	20	25	10	12	50	25	25
# of louvers	15	31	15	25	31	20	10	39	31	31
Resistance of contact (μΩ)	19.33	9.68	23.33	10.00	9.68	17.50	30.00	10.26	10.65	4.52
Current Capacity of contact	645	1178	435	1075	1085	460	400	1560	1550	2790
Power dissipation at 400 A (W)	3.09	1.55	3.73	1.60	1.55	2.80	4.80	1.64	1.70	0.72
Voltage drop (mV)	7.73	3.87	9.33	4.00	3.87	7.00	12.00	4.10	4.26	1.81
Sliding force of contact (N)	89.25	97.65	105.00	918.75	352.63	112.00	24.50	136.50	54.25	108.50

The question of how to choose a Multilam option based on design constraints and priorities was an important one to answer. The solution came in the form of Multilam Contact Design Graphs. Eight graphs were made to aid choice and design of a contact. These graphs, enabled the designer to choose the right Multilam contact for a given purpose and set of priorities.

4.3 Compact Multilam design example

Given the shipboard environment and the premium on space, it was desired to select contacts that were as compact as possible. The Multilam Contact Design Graphs were used to select Multilam variants that were competitive against each other and would fulfill the desire to make a compact connector. Below details the process of selecting Multilam variants for a 1000 A contact.

First using the Total Current Capacity v. Diameter graph the Mulitlam variants were selected with the corresponding diameter given the required current capacity. Figure 4-7 displays the graph and the horizontal black design line at 1000 A. Four Multilam variants intersected the design line and were selected to proceed to the second step of the process.

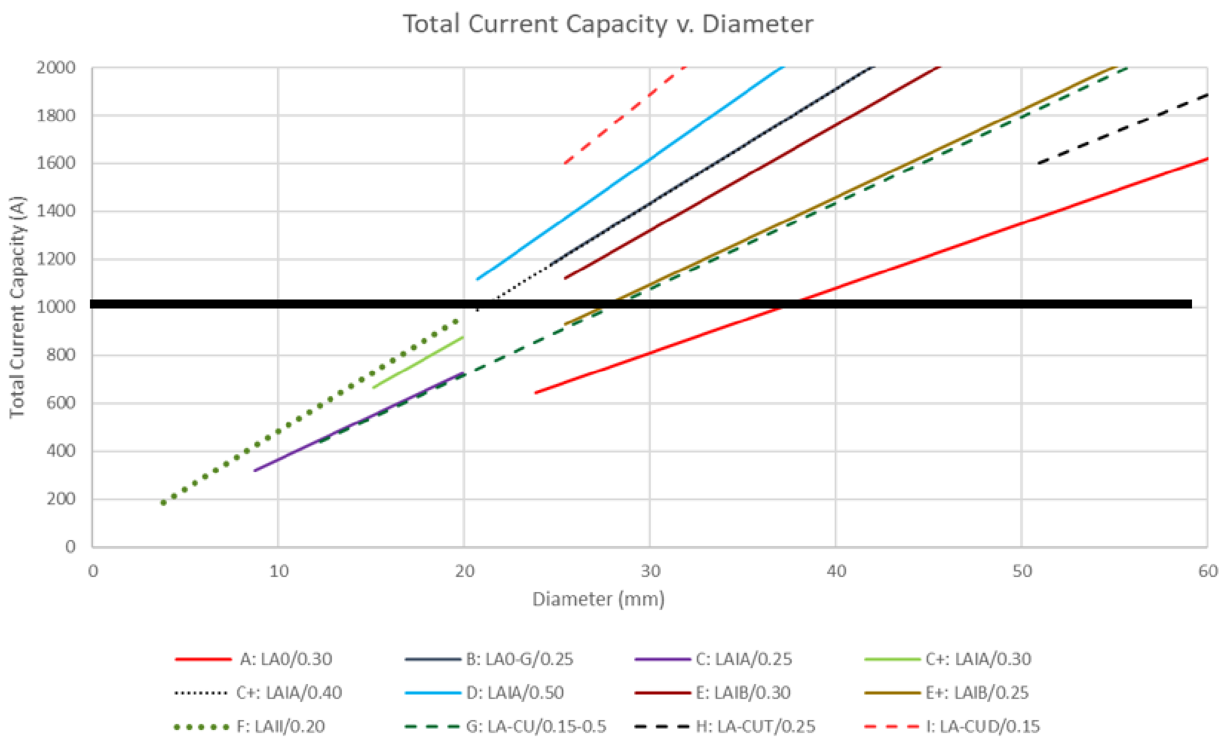


Figure 4-7:Multilam Total Current Capacity v. Diameter design graph, 1000 A black horizontal design line

The sliding force for each contact at the given current capacity was identified using the Sliding Force v. Total Current Capacity design graph, Figure 4-8.

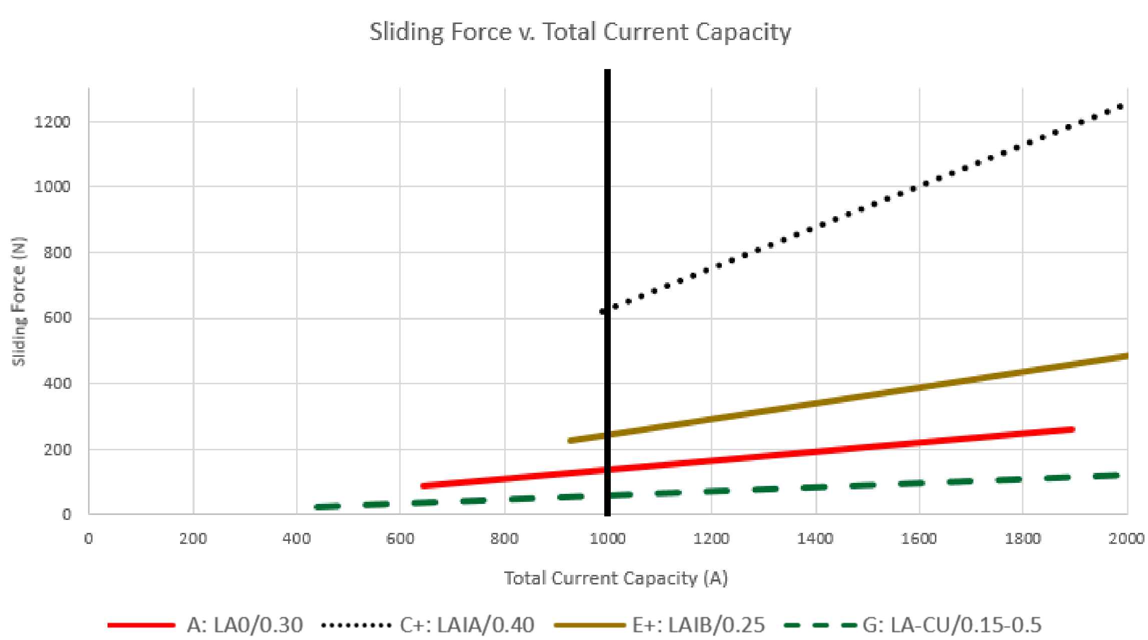


Figure 4-8: Multilam Sliding Force v. Total Current Capacity design graph, 1000 A black vertical design line

Finally, the power dissipation at the design current, 1000 A, was identified and compared on the Power Dissipation v. Sliding Force graph, Figure 4-9. Black stars indicate the 1000 A point design for each variation.

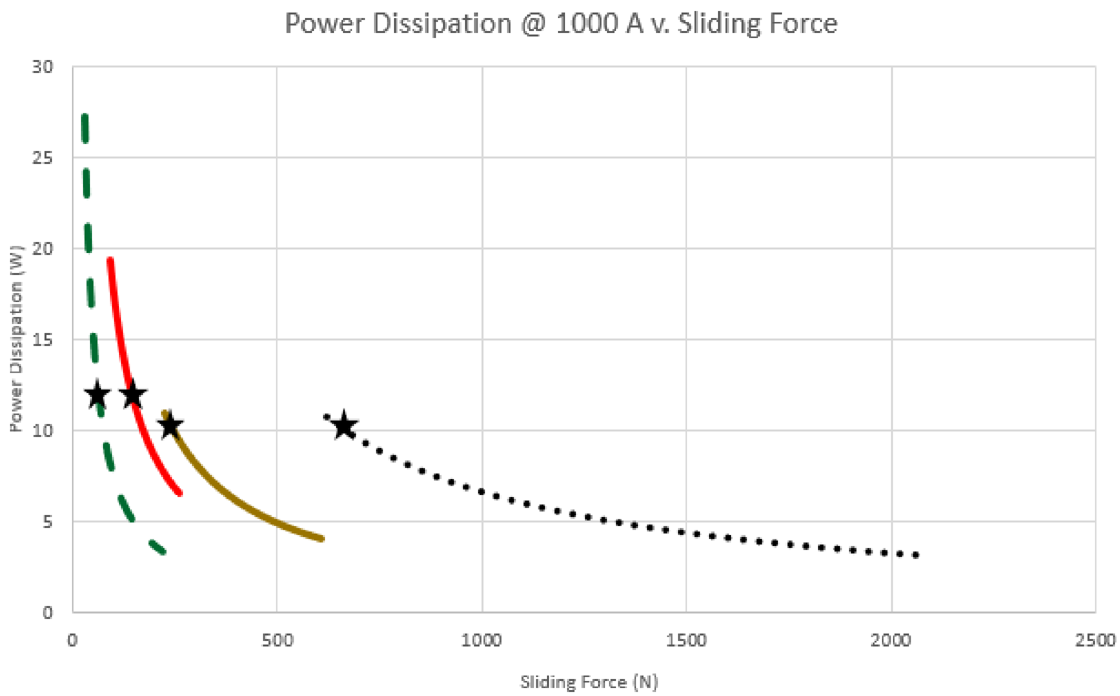


Figure 4-9: Multilam Power Dissipation v. Sliding Force design graph. Stars indicated 1000 A contacts.

A summary of the findings is in Table 4-3. Option G had the lowest sliding force, but had a high-power dissipation. If size was truly the driving factor option C+ was the most compact, but at the cost of a high sliding force. If there were a power dissipation constraint for 10 W, option E+ would be the only choice. This method of design selection was valuable as it down selected variants from a multitude to just a few which could be assessed according to particular constraints and priorities. Further Multilam design summary examples are in Appendix B.

Table 4-3: Design summary of 1000 A Mulitlam options

Type	# of louvers	Round Contact: diameter (mm)	Current Capacity of contact (A)	Resistance of contact (μΩ)	Sliding force of contact (N)	Power dissipation (W)
A: LA0/0.30	24	38.22	1032	12.08	142.8	12.08
C+: LAIA/0.40	27	21.50	1026	10.37	642.6	10.37
E+: LAIB/0.25	35	27.87	1015	10.00	245	10.00
G: LA-CU/0.15-0.5	25	27.87	1000	12.00	61.25	12.00

4.4 Other Louver Contacts

It was beneficial to find a way to compare and design a contact with different Multilam louver variants. The same process was applied to non-Multilam louver contacts. The idea of breaking down the electrical and physical properties per louver was applied to other commercial contacts that used louver electrical mechanisms. Contacts were reversed engineered using the known contact characteristics and values of: rated current, contact resistance, contact diameter, number of louvers, and insertion force.

The process started with the known characteristics to first determine the louver pitch (contact spacing) using equation (1). The resistance of one louver, equation (2), the rated current of one louver, equation (3), and the contact force per louver, equation (5), all of which could then be found based on the known parameters and louver pitch. This broke down the characteristics of the contact into per louver form, just as Multilam contact characteristics were listed. The information could then be linearly extrapolated using the same equations and process as described in section 4.2 to form other size and rated contacts that would use the same louver technology. Before this process, commercial contacts were rated for many different currents and there was no way to directly compare electrical contact designs against one another. Using this process different contact louver technology could be compared across a common parameter to determine a best option to proceed further into the design process.

4.4.1 Introduction to the other Louver Contacts

Twelve contacts were selected for further investigation. The criteria for the twelve selected were to be a split socket/plug, a leaf spring socket, or torsion louver socket/plug in order to employ the methodology laid out earlier. There also had to be enough information provided by the manufacturer in order to conduct the analysis. The pieces of information necessary were: rated current, contact resistance, contact diameter, number of louvers, and insertion force of the contact.

The twelve contacts are pictured in Figure 4-10 and Figure 4-11 and labeled with the current rating the original contact was manufactured to handle. There are some distinctions to note for several of the contacts. The Radsok contact was a louver system much like the Multilam, that could be applied to a pin and socket. It was an electrical contact technique that could be compared directly to the Multilam contacts. Its electrical characteristics were provided for the contact technique alone.

Radlok was a full connector that employed Radsok technology, therefore the Radlok could be directly compared to other connectors because the electrical data such as electrical resistance applied to the full connector, louvers and bulk resistance, much like the other electrical connectors. Turntac, Lamtac and Springtac came in a range of sizes able to accommodate a range of currents. The Turntac contact was analyzed at the 125 A rating corresponding to the 10 mm size socket.

The number of louvers changed nonuniformly or linearly with size in Lamtac and Springtac so the methodology was not applied to these two contacts. The manufacturer, ODU, provided size, force, current, and resistance data at each size of contact. This information was used to compare them to other full connectors. The per louver information was assessed at a contact size for which the number of louvers were also known; the 5 mm 135 A Springtac, and the 4 mm 115 A Lamtac.

Finally, mating force came in two variations, connector mating force and sliding force. As discussed in 2.3, the sliding force or electrical mating force was the maximum friction force induced by the contact mating process. The connector mating force or plug-in force was the maximum force needed in order to both electrically mate the contact as well as mechanically mate the connector. The plug-in force took into account weather proofing mechanisms that increased the mechanical mating force. DW1, HBB, Han S, and Kona only provided plug-in mating forces while all other manufacturers provided sliding force data.

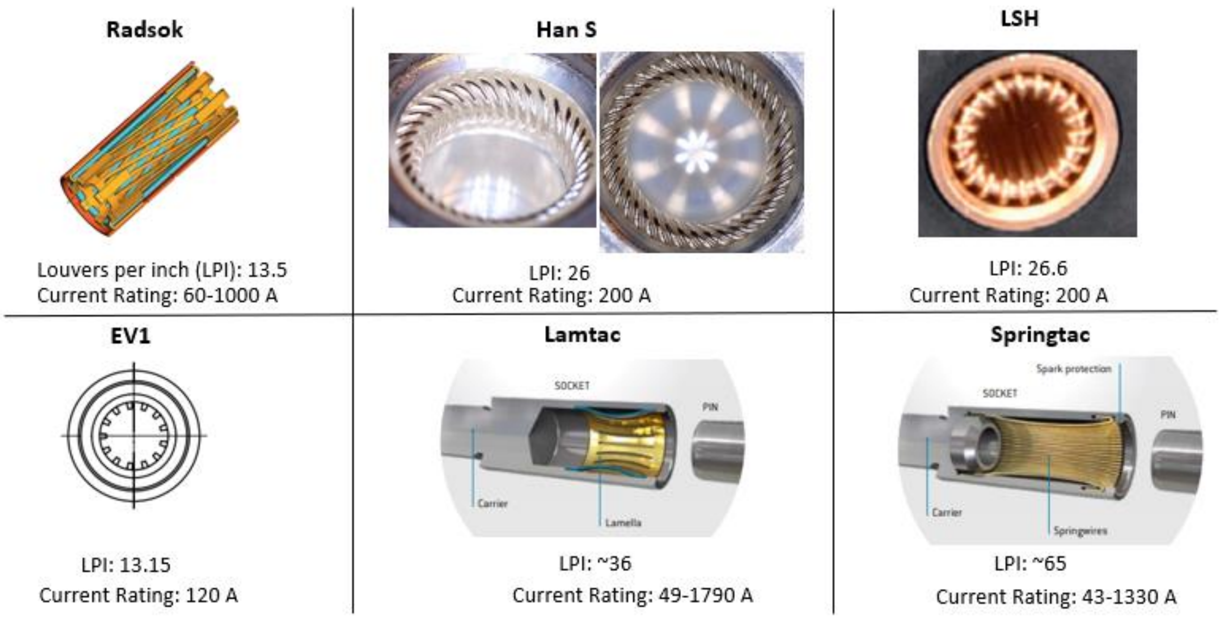


Figure 4-10: Selected louver contacts for reverse engineered per louver analysis

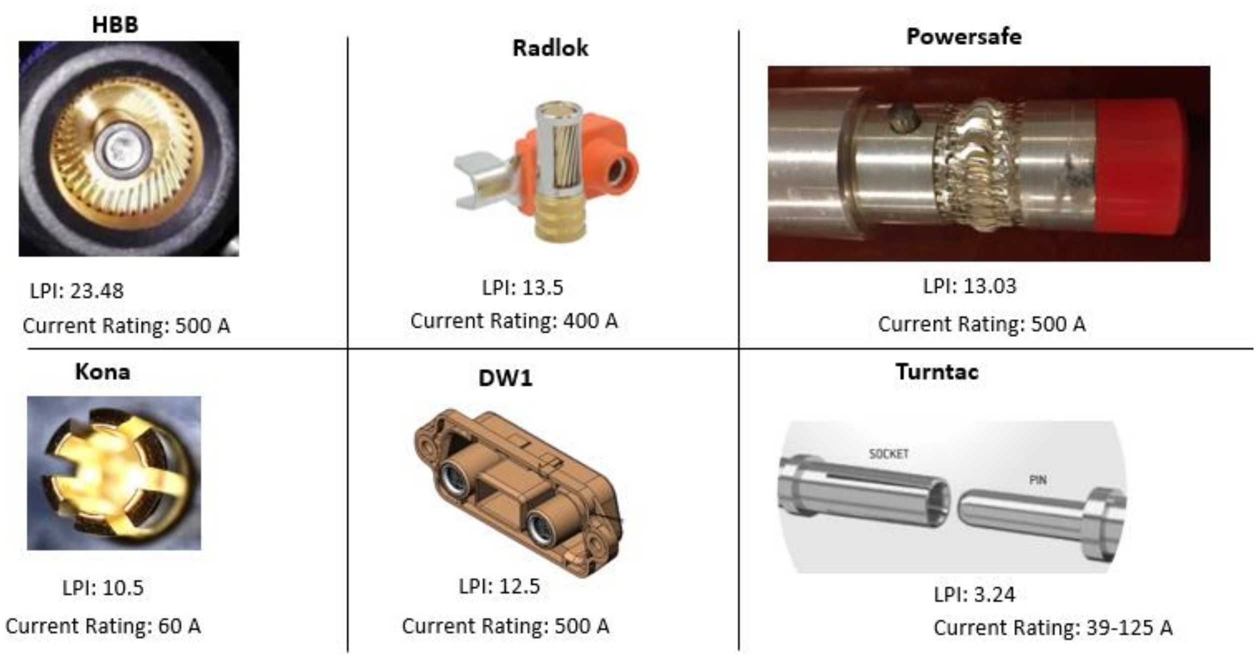


Figure 4-11: Selected louver contacts and connectors for reverse engineered per louver analysis

4.4.2 Other Louver Contacts per louver results

By breaking down the electrical and force information of the contacts into a per louver basis, extrapolated data could be used to predict the size, force, and electrical characteristics of contacts outside of the products offered by existing manufacturers. By doing so, the technology and technique of an existing commercial contact could be selected in order to pursue the design of a new contact. Table 4-4 displays the results of the per louver comparison.

Table 4-4: Per louver comparison between selected louver connectors

Connector	Rated current of one louver (A)	Louver pitch (spacing) (mm)	Louvers per inch	Resistance of one louver (mΩ)	Electrical Data for:	Contact force per louver (N)	Force Note:
Springtac (5 mm diameter)	3.38	0.39	64.71	8.00	Assembly	1.29	Electric
Lamtac (4 mm diameter)	6.39	0.70	36.40	5.40	Assembly	1.59	Electric
LSH Series	10.00	0.95	26.61	2.00	Assembly	6.29	Electric
HBB Series (size 21)	13.89	1.08	23.48	1.80	Assembly	27.78	Mechanical
DW1	19.23	2.03	12.54	5.20	Assembly	43.96	Mechanical
Powersafe	17.24	1.95	13.03	14.50	Assembly	6.40	Electric
Han S	5.26	0.98	25.98	11.40	Assembly	1.13	Mechanical
EV1	9.23	1.93	13.14	6.50	Assembly	1.01	Electric
Kona	10.00	2.42	10.49	12.00	Assembly	23.81	Mechanical
Turntac (10 mm diameter)	62.50	7.85	3.24	0.50	Assembly	8.57	Electric
Radlok	14.29	3.14	18.85	6.60	Assembly	8.33	Mechanical
Radsok	16.88	3.14	18.85	0.72	Louvers	8.33	Electric

Using the information in Table 4-4, design graphs similar to those in section 4.3 were developed. A connector could be selected for an application through the use of the design graphs. The 1000 A application example is illustrated below.

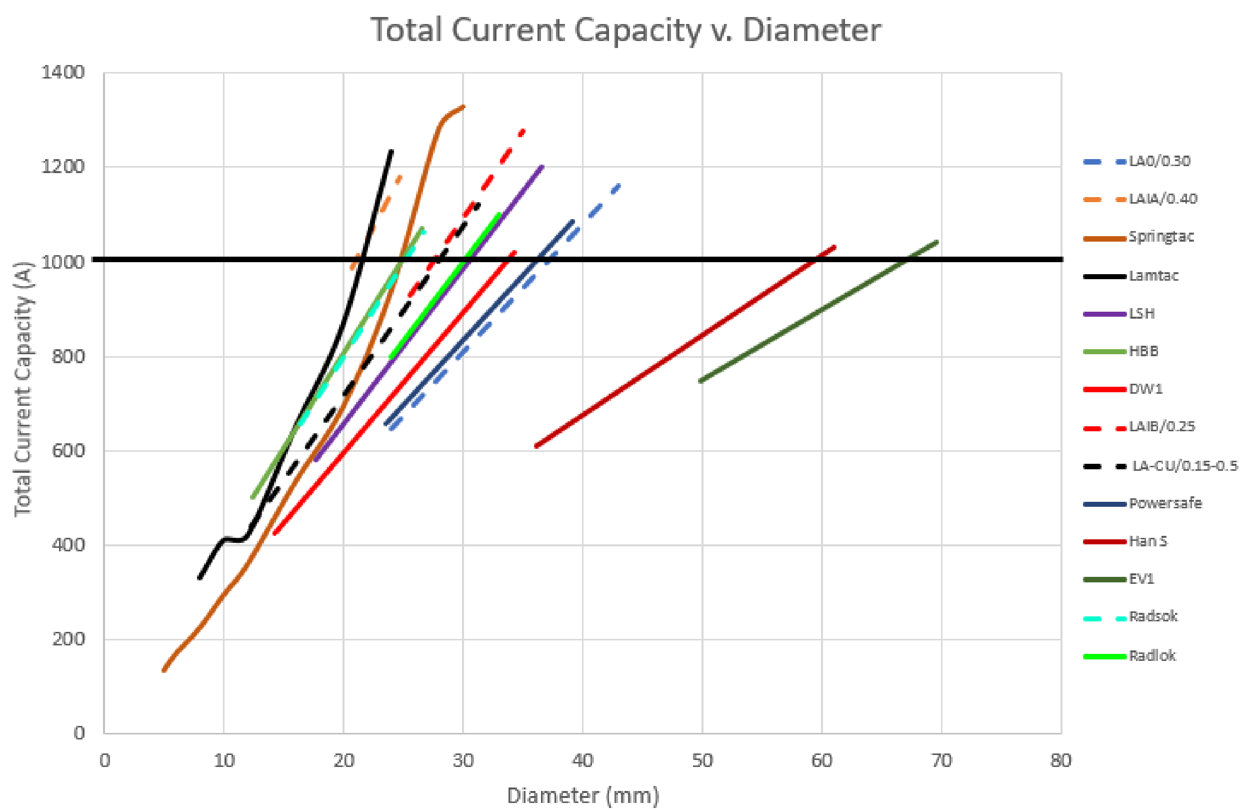


Figure 4-12: Louver Contacts Total Current Capacity v. Diameter design graph, 1000 A black horizontal design line

As before, the black horizontal line delineates the design line of 1000 A. The solid lines are louver contacts with electrical data for the full connector. Contacts plotted in a dashed line, such as the Multilam louvers, were louver only electrical data meaning the rest of the bulk resistance that would make up a contact was not taken into account. EV1 and Han S stood out as large diameter contacts compared to the majority the other contacts which ranged from a diameter of 20-38 mm.

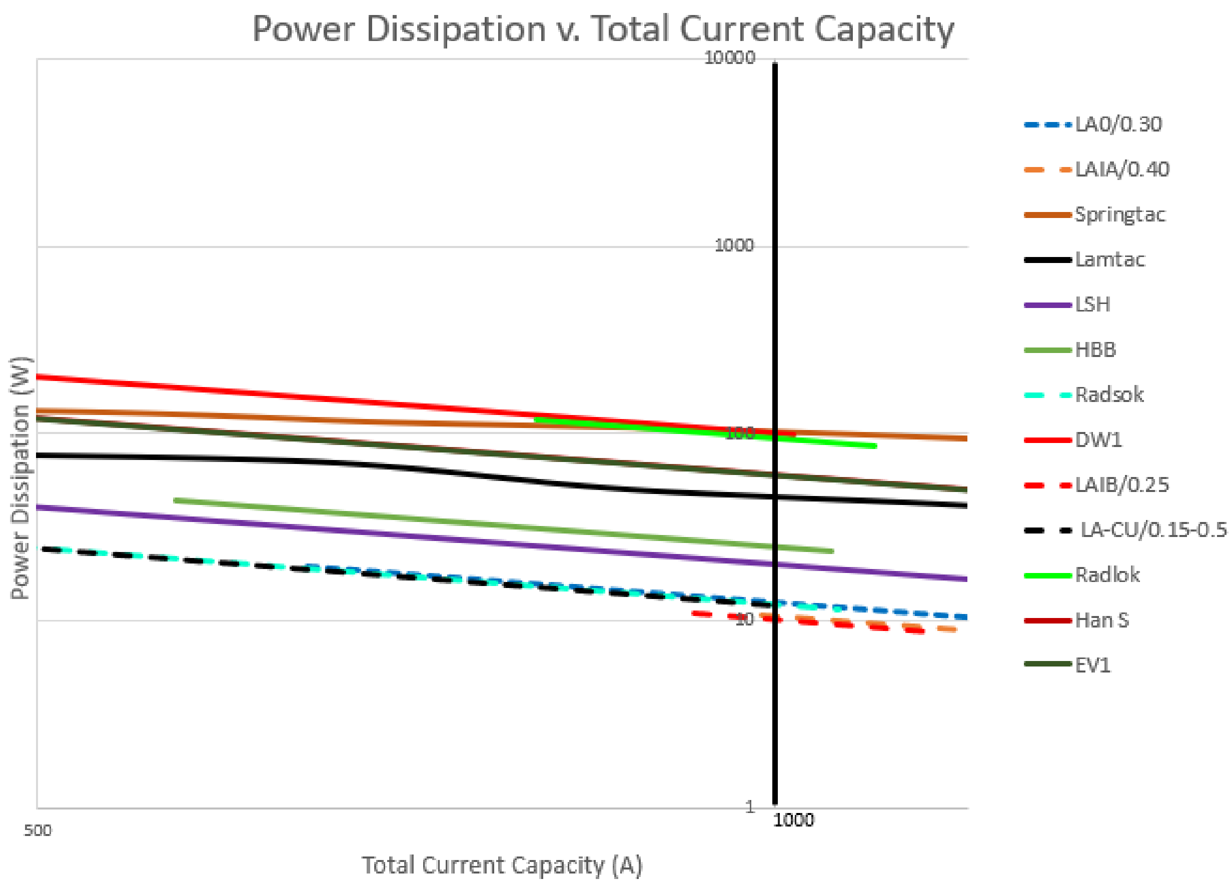


Figure 4-13: Louver Contacts Total Power Dissipation v. Total Current Capacity Log- Log design graph, 1000 A black vertical design line

Figure 4-13 shows the power dissipated by each type of contact plotted against the total current capacity of the contact. The design line is indicated by the vertical black line at 1000 A. All of the louver only contacts, dashed lines, had lower power dissipation levels than full contacts. This was important to note as they did not include the bulk resistance like the full contacts. It was expected that once they are paired with a pin and socket, the source of the bulk resistance, the resistance curves would move up on the graph. Radsok for instance was used in the Radlok connector, due to the bulk resistance not accounted for in Radsok, the Radlok power dissipation was an order of magnitude larger.

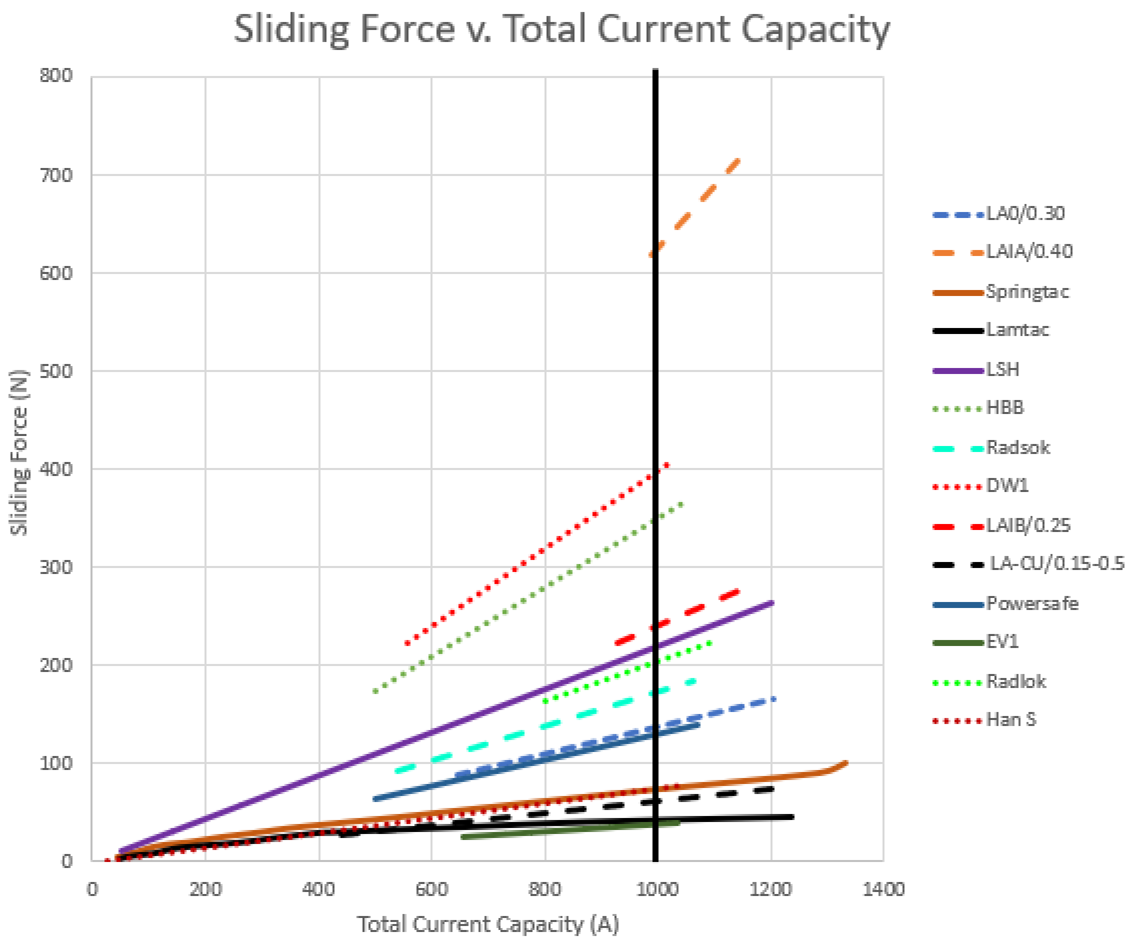


Figure 4-14: Louver Contacts Sliding Force v. Total Current Capacity design graph, 1000 A black vertical design line

Figure 4-14 graphically shows the sliding force associated with the 1000 A contacts. Dashed lines are again louvers alone, however unlike before these can be directly compared to the solid lines because they are just the sliding force to mate the electric contacts. The dotted lines of HBB, DW1, Radlok, and Han S graph the plug-in force.

Radlok did not use the same size diameter contact to make a 1000 A contact as the Radsok louvers alone would imply. Radlok employed a larger Radsok due to derating by the manufacture. It was unknown if this was done as a result of heating in the louvers, bulk material, or casing, or if it was done just as a precaution for the application of the Radlok.

Derating is the technique of operating contacts below their maximum power rating taking into account ambient temperatures, cooling mechanisms, and self-heating. The International Electrotechnical Commission (IEC), an international standards organization for electrotechnology offers a process to test a connector and develop derating curves [65]. As the process explains: "current carrying capacity is limited both through the thermal properties of the materials used for the contacts and connections and the insulation elements. Thus, it is a function of both the self-heating and the ambient temperature at which the component part is operated" [65]. As an example, the Radsok derating curve is shown in Figure 4-15. As ambient temperature increases the current capacity decreases. A change in the insulation, housing, or termination method would require reassessment of the derating curve. When the commercial connector review was conducted derating figures were not always available; therefore, current ratings presented in this paper were taken from manufacture advertised ratings and not adjusted according to any derating curves.

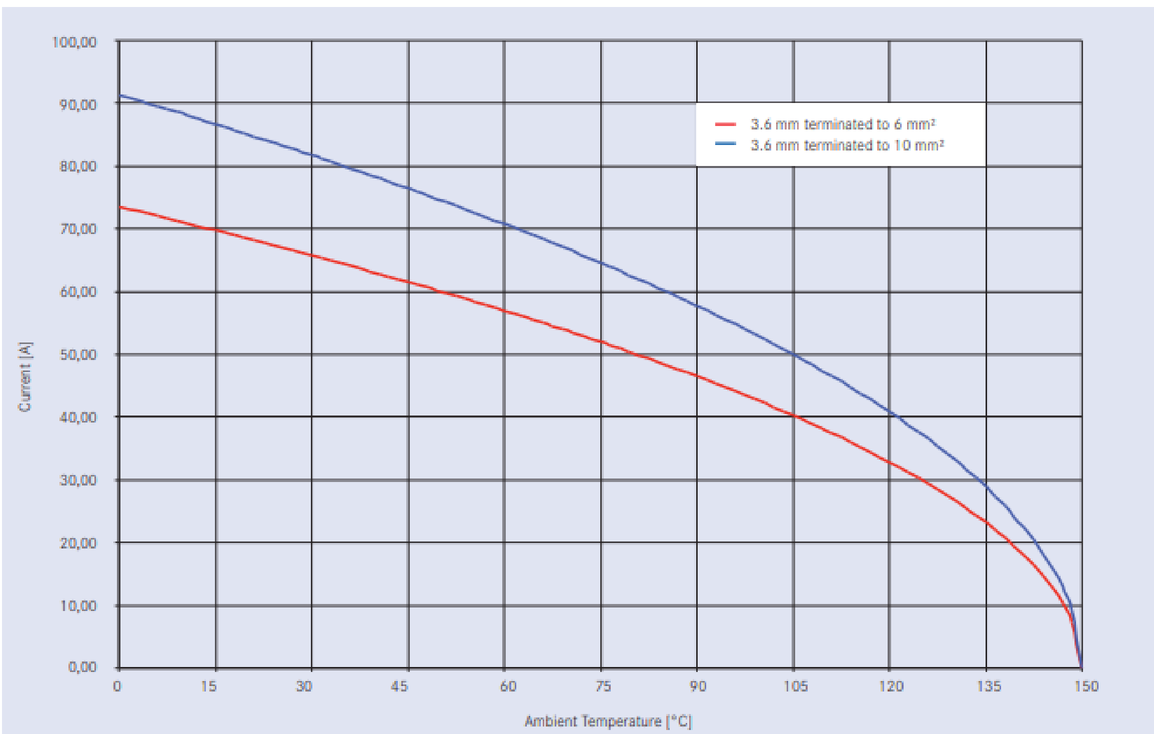


Figure 4-15: Derating curve for the 3.6 mm Radsok [66]

The design tools presented in this thesis could be improved if all the contacts were compared at the same ambient temperature condition. This would improve the comparison between off the shelf contacts and connectors by comparing them at the operating temperature they would be expected to operate in the shipboard environment.

Tabulated characteristics of the various contacts are displayed in Table 4-5. The top half of the table, orange and green rows, represent contact information for louver and bulk electrical data. The lower half of the table in gray represent contact information for the louver only designs.

Table 4-5: 1000 A louver contact design characteristics.
*Extrapolated data from baseline connector, †Full connector plug-in force

	# of louvers	Round Contact "Diameter" (mm)	Current Capacity of contact (A)	Resistance of contact (μΩ)	Sliding force of contact (N)	Power dissipation (W)
Springtac		28	1285	90	90	90
Lamtac		24	1235	40	45	40
LSH*	100	30.4	1000	20	220	20
HBB*	72	24.8	1000	25	350†	25
DW1*	52	33.54	1000	100	400†	100
Powersafe*	58	36	1000	250	130	250
Han S*	190	59.15	1000	60	75†	60
EV1*	109	67.08	1006.15	59.63	38.55	59.63
Radlok*	70	30.00	1000	94.29	204.17†	94.29
Radsok*	60	25.75	1012.5	12	175	12
LA0/0.30	24	38.22	1032	12.08	142.80	12.08
LAIA/0.40	27	21.50	1026	10.37	642.60	10.37
LAIB/0.25	35	27.87	1015	10	245	10
LA-CU/0.15-0.5	25	27.87	1000	12	61.25	12
LAIB/0.30	32	25.48	1120	9.38	364	9.38
LAIA/0.50	26	20.70	1118	9.62	955.50	9.62

Another graphical way to easily interpret the data was through a bar chart such as Figure 4-16. The diameter of the contact and power dissipation were plotted using the left-hand vertical axis and the sliding force of the contact was plotted using the right-hand axis. The louver only contacts without other parts are depicted in striped bars. In this graph it was easy to compare the various contacts at a specific current rating.

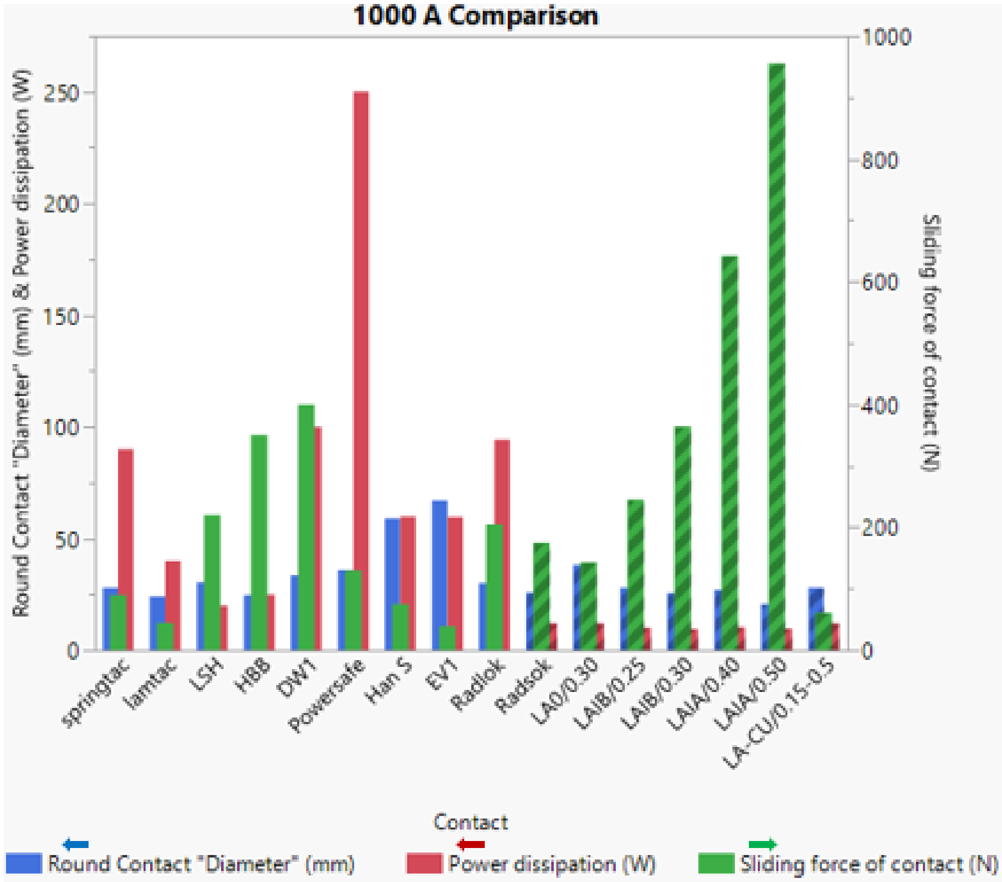


Figure 4-16: Bar Chart comparison for 1000 A louver contact designs. Louver only electrical data in striped.

This design tool was very useful when choosing a contact that needed to optimize a specific characteristic. For example, if sliding force needed to be the lowest possible, EV1 and Lamtac stood out on the graph for having the lowest mating force. Size and power dissipation could be easily compared according to the other design priorities of the application.

4.5 Development of Figures of Merit

Using per louver electrical information was important to compare contacts at a specific current rating. Another broader non-dimensional practical way to compare like contacts to one another would be beneficial to the design process. This led to the development of four separate Figure of Merit (FOM). To establish the FOM values, key connector performance parameters are first normalized by a per-unit-length quantification, and then these normalized per length values are combined to set several different FOMs.

4.5.1 Per Linear Inch Comparison

The first step was to compare all contact characteristics on a uniform per length dimension. Per louver was not the best comparison method since each contact employed different size louvers and different spacing between each louver. By comparing on a per linear inch basis, a strip of contact louvers of one type could be directly compared to other contacts. Table 4-6 shows the per inch length characteristics of full contacts, and Figure 4-17, Figure 4-18, and Figure 4-19 graphically compare the three characteristics of maximum current per inch, resistance per inch, and sliding force per inch. Current per inch and resistance could be directly compared because all the contacts included bulk resistance and a full connector. Sliding force per inch was divided into two categories shown in blue and green, plug-in force and electrical contact sliding force.

Table 4-6: Per inch length characteristics of full contacts
†Indicates sliding force is for full plug-in force

Connector	Whole number of louvers per inch	Current per inch (A/in)	Resistance per inch (mΩ/in)	Sliding Force per inch (N/in)	Maximum Power Dissipated per inch^3	Maximum Power Dissipated per inch (W/in)
Springtac (5 mm diameter)	64.00	216.00	0.13	28.80	5.83	0.086
Lamtac (4 mm diameter)	36.00	230.00	0.15	20.00	7.94	0.043
LSH Series	26.00	260.00	0.08	57.20	5.20	0.185
HBB Series (size 21)†	23.00	319.44	0.08	223.61	7.99	0.557
DW1†	12.00	230.77	0.43	184.62	23.08	0.250
Powersafe	13.00	224.14	1.12	29.14	56.03	1.042
Han S†	25.00	131.58	0.46	9.87	7.89	0.290
EV1	13.00	120.00	0.50	4.60	7.20	0.421
Kona†	10.00	100.00	1.20	83.33	12.00	
Turntac (10 mm diameter)	3.00	187.50	0.17	9.00	5.86	
Radlok†	18.00	257.14	0.37	52.50	24.24	1.059

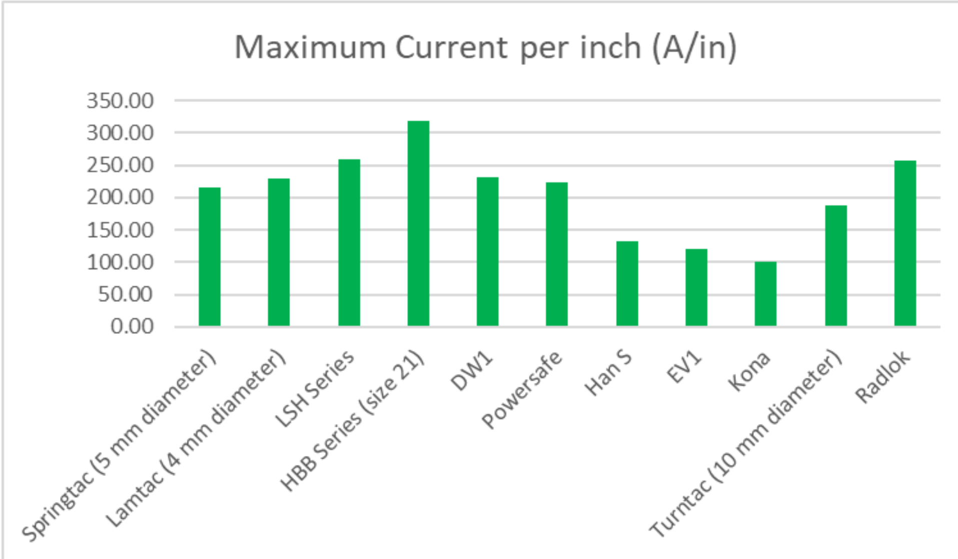


Figure 4-17: Maximum Current per inch of full connectors

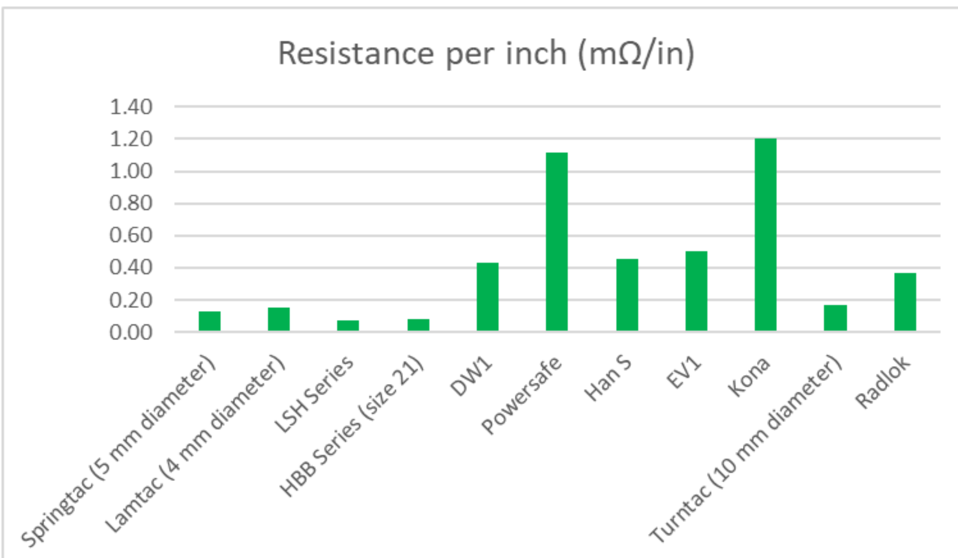


Figure 4-18: Resistance per inch of full connectors

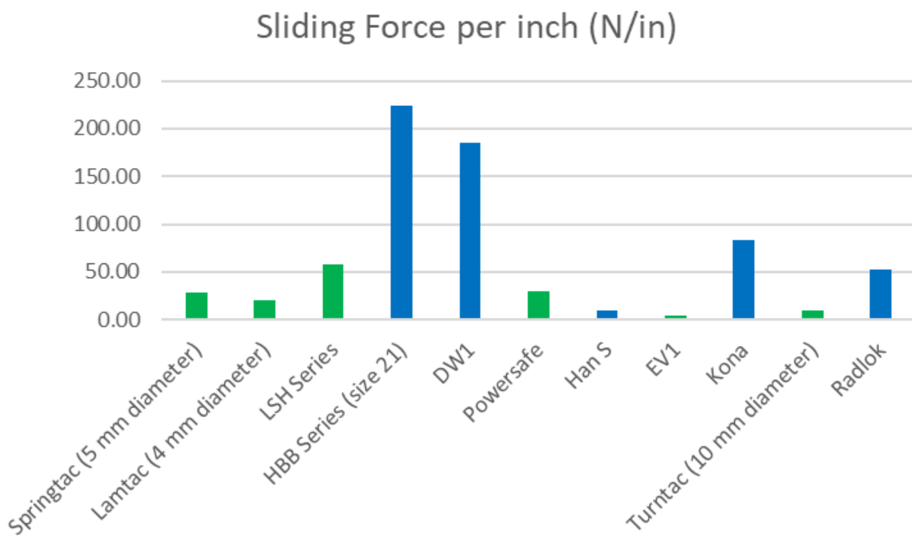


Figure 4-19: Sliding force per inch of full connectors
Green columns represent plug-in force connector data. Blue columns represent data associated with louver sliding forces only.

Table 4-7 shows per inch characteristics of the louver only contacts. All louvers can be directly compared to each other graphically in Figure 4-20, Figure 4-21, and Figure 4-22.

Table 4-7: Per inch length characteristics of louver only contacts

Connector	Whole number of louvers per inch	Current per inch (A/in)	Resistance per inch (mΩ/in)	Sliding Force per inch (N/in)	Maximum Power Dissipated per inch^3	Maximum Power Dissipated per inch (W/in)
Radsok	18.00	303.84	0.04	52.50	3.69	0.161
LA0/0.30	5.00	215.00	0.06	29.75	2.68	0.065
LA0-G/0.25	8.00	304.00	0.04	25.20	3.47	0.067
LAIA/0.25	10.00	290.00	0.04	70.00	2.94	0.040
LAIA/0.30	10.00	350.00	0.03	113.75	3.68	0.060
LAIA/0.40	9.00	342.00	0.03	214.20	3.64	0.079
LAIA/0.50	10.00	430.00	0.03	367.50	4.62	0.125
LAIB/0.20	11.00	308.00	0.04	57.75	3.45	0.038
LAIB/0.25	10.00	290.00	0.04	70.00	2.94	0.040
LAIB/0.30	12.00	420.00	0.03	136.50	4.41	0.072
LAII/0.20	16.00	368.00	0.02	89.60	2.96	0.026
LA-CU/0.15-0.5	7.00	280.00	0.04	17.15	3.36	0.062
LA-CUT/0.25	14.00	560.00	0.03	49.00	8.96	0.722
LA-CUD/0.15	13.00	650.00	0.03	36.40	10.73	0.224

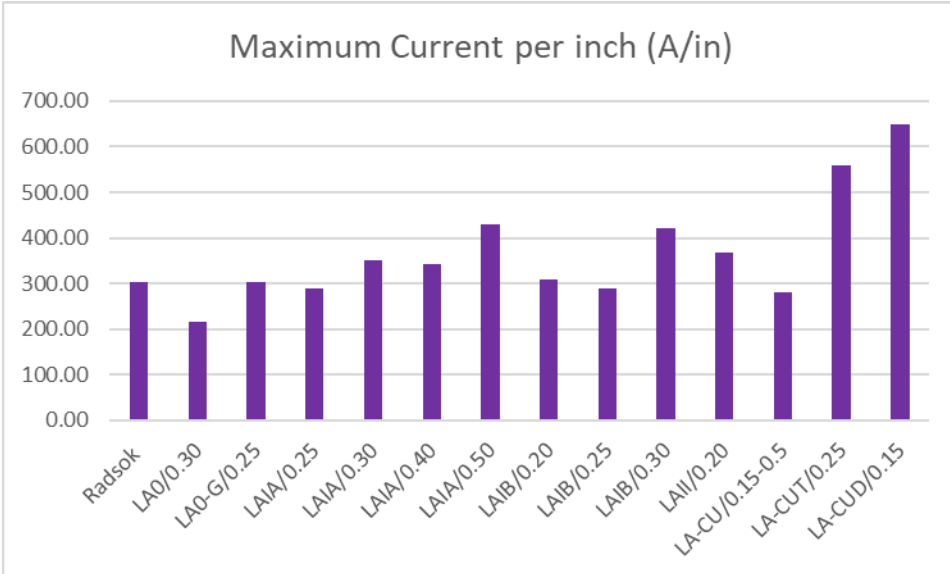


Figure 4-20: Maximum current per inch of louver only contacts

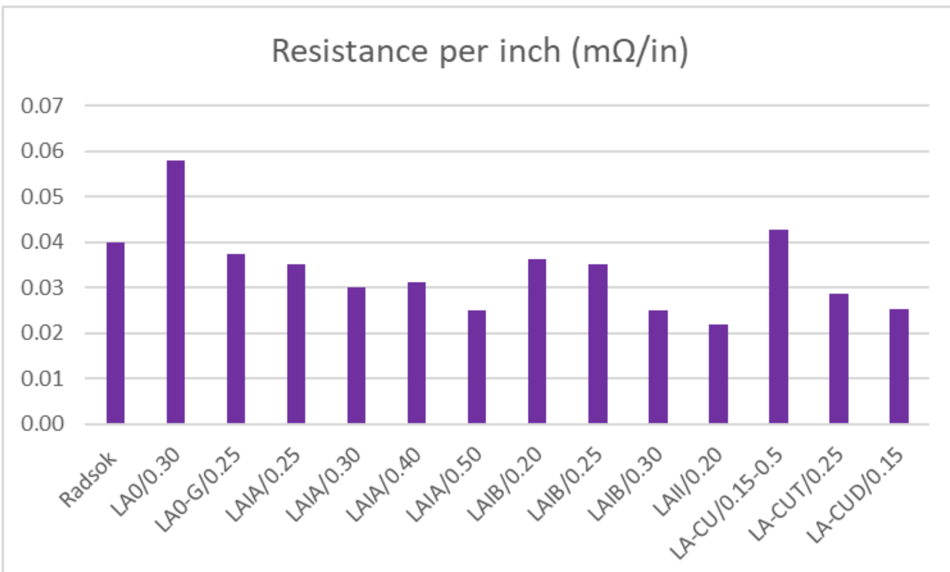


Figure 4-21: Resistance per inch of louver only contacts

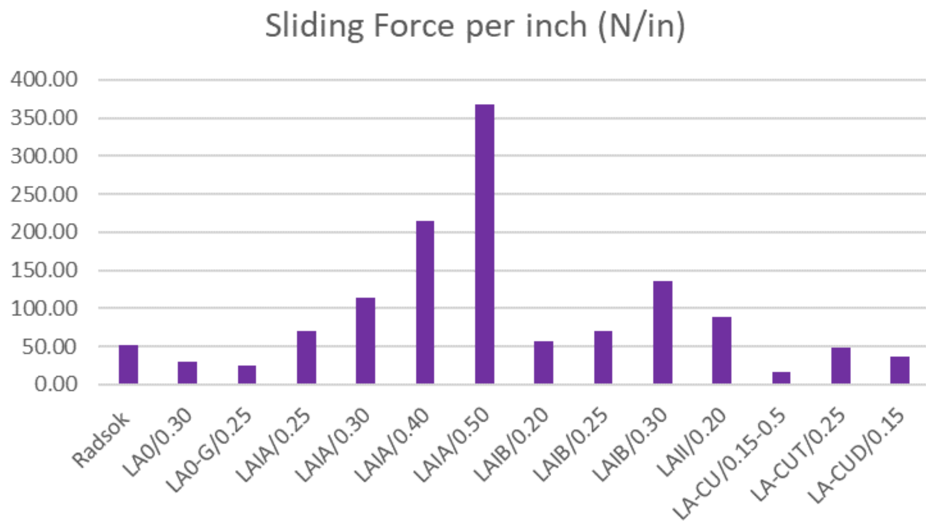


Figure 4-22: Sliding force per inch of louver only contacts

Turntac and Kona were split plug/socket contacts and were not analyzed for maximum power dissipation per inch. All other contacts were using equation (6).

R_{in}=Resistance per inch (Ω/in)
I_{in}=Maximum Current per inch (A/in)
P_{in}=Power dissipated per inch (W/in)
t=thickness of louver
w=width of louver

$$P_{in} = {I_{in}}^2 * R_{in} * (2t * w) \qquad (6)$$

The thickness and width dimensions of the louvers are depicted in Figure 4-23, Figure 4-24, and Figure 4-25. Another way to state "w" would be the depth of the louvers in the contact assembly.

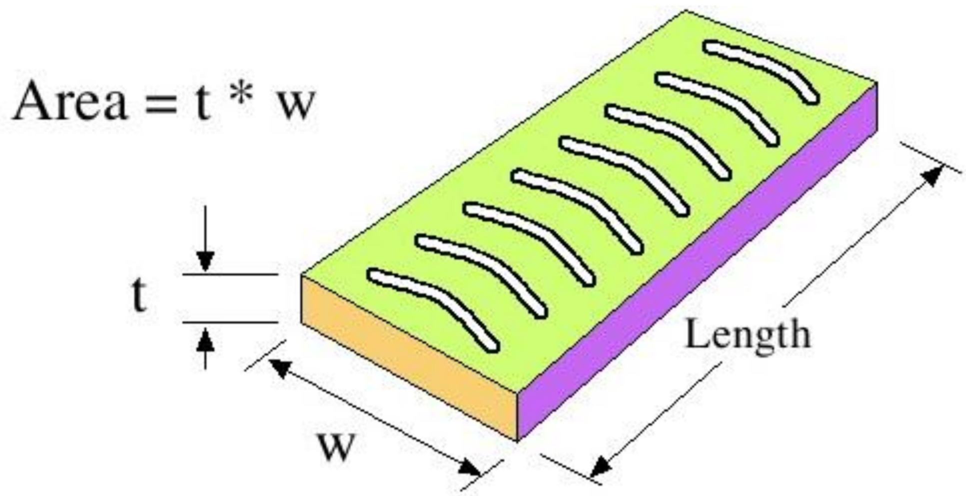


Figure 4-23: Louver thickness, width, and height measurement dimensions

Figure 4-24: The width dimension illustrated on louvers in a socket

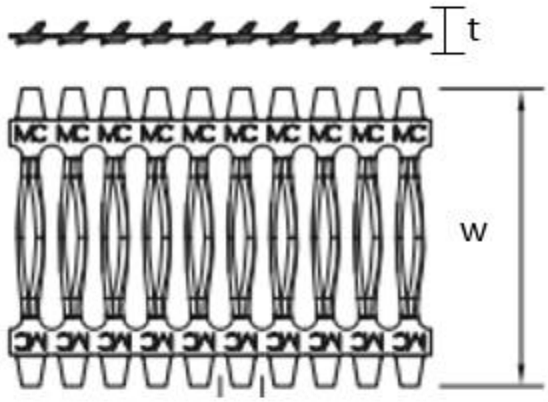


Figure 4-25: The width and thickness dimensions of a Multilam louver

The results of the power dissipated per inch are graphically depicted in Figure 4-26 and Figure 4-27.

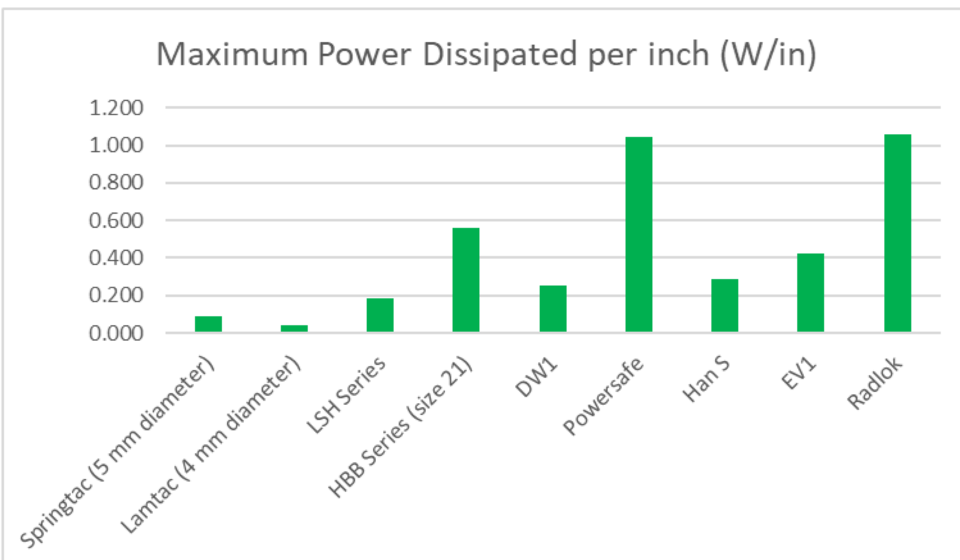


Figure 4-26: Maximum Power Dissipated per inch of full connectors

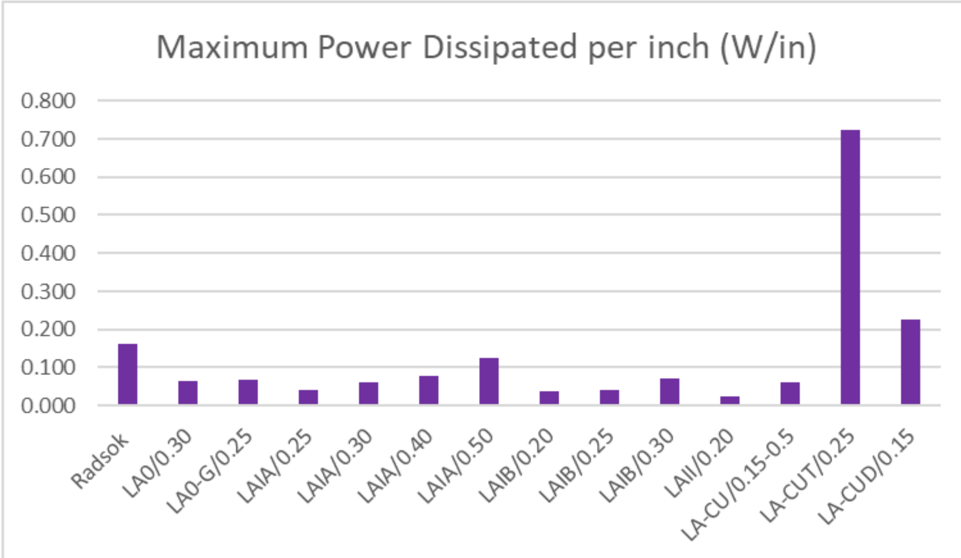


Figure 4-27: Maximum Power Dissipated per inch of louver only contacts

4.5.2 Figures of Merit

The FOMs were composed with non-length-dimensional combinations of quantities so that absolute size effects were minimized. They were made to be functional for designers to select a contact which would best suit their application without having to go through the comparison design graphs and tables previously presented. The FOMs were weighted in such a way that the higher the non-dimensional FOM score the better the contact. The three definable, measurable and useful parameters used in creating the FOMs were:

1) Rin=Resistance per inch (mΩ/in)
2) Fin= Sliding force per inch (N/in)
3) Iin=Current per inch (A/in)

The best connector would have a high current per inch, low resistance per inch and low sliding force per inch. Many different non-dimensional combinations were evaluated in the development of the FOMs. In the end, three FOMs were created that weighed one characteristic as a priority to help a designer concerned about a specific aspect of the contact. A fourth FOM was created as an all-around best contact.

The first Figure of Merit, FOM1, weighed current per inch more than sliding force or resistance. This FOM would be especially useful for a designer looking to make a space efficient design, prioritizing a small size while still balancing power loss and sliding force. FOM1 was computed using equation (7).

$$FOM1 = \frac{{I_{in}}^2}{R_{in} * F_{in}} \quad (\text{A}^2/\ \text{m}\Omega\ \text{N}) \qquad (7)$$

FOM2, equation (8), was weighed toward minimizing the resistance of the contact and consequently power loss.

$$FOM2 = \frac{{I_{in}}^{\frac{3}{2}}}{R_{in} * \sqrt{F_{in}}} \quad (\text{A}^{3/2}/\ \text{m}\Omega\ \text{N}^{1/2}) \qquad (8)$$

FOM3, equation (9), prioritized sliding force, meaning contacts with lower sliding force had higher FOM3 scores while still balancing current density and resistance.

$$FOM3 = \frac{{I_{in}}^{\frac{3}{2}}}{F_{in} * \sqrt{R_{in}}} \quad (\text{A}^{3/2}/\ \text{m}\Omega^{1/2}\ \text{N}) \qquad (9)$$

The last FOM, FOM4 was computed using FOM1, FOM2, and FOM3. It was derived from the average of the other three normalized FOMs. It was calculated by normalizing each individual FOM score of the contact, dividing the FOM score by the summation of all contact FOM scores for that particular FOM. The resulting normalized FOM1, FOM2, and FOM3 scores for a particular contact were then averaged to produce FOM4. FOM4 scores lay between 0 and 1, the higher being better. Only like contacts can be used to normalize against each other, thus full contacts and louvers were calculated separately. FOM4 worked best when a robust number of contacts with like characteristics were compared. In an effort to do so, in this study as an approximation sliding force data was halved in FOM computations for contacts that only had plug-in force information available.

4.5.3 Figures of Merit Results

The results of the full connector FOMs are graphed in Figure 4-28, Figure 4-29, Figure 4-30, and Figure 4-31.

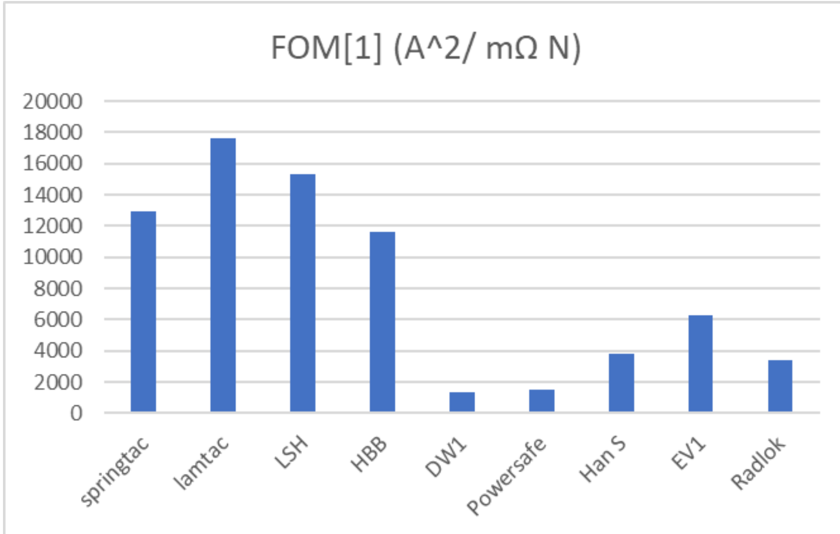


Figure 4-28: FOM1 results for full connectors

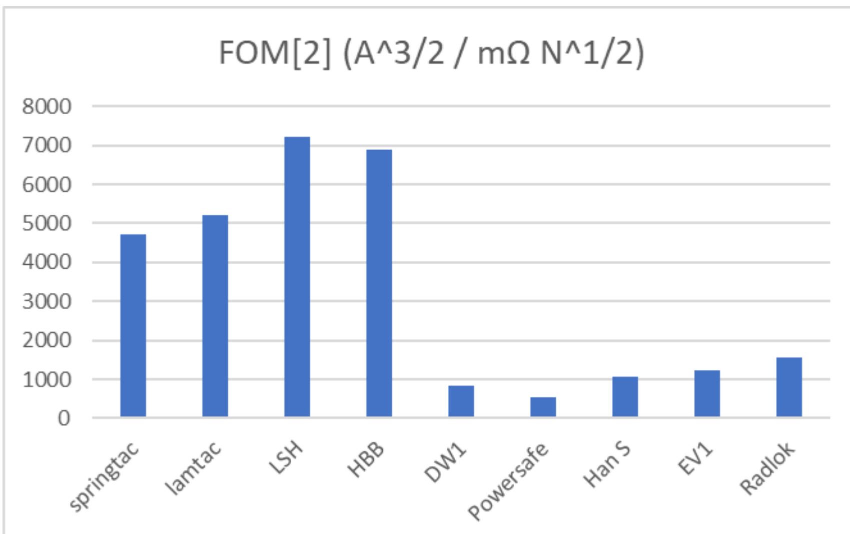


Figure 4-29: FOM2 results for full connectors

Using the results of FOM1 and FOM2 to compare connectors it was evident that they could be broken into two distinct groups, the first group of: Springtac, Lamtac, LSH, and HBB, and the other group consisting of the remaining five. The first four standout as superior connectors except when sliding force was a major priority as seen by the results of FOM3. HBB scored low, penalized for its high mating force and EV1 rose to second because it had the lowest mating force per inch of any contact.

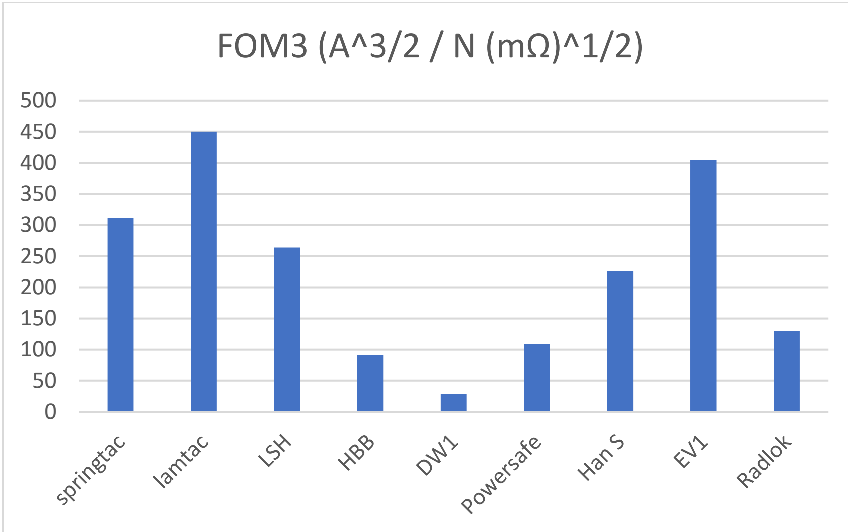


Figure 4-30: FOM3 results for full connectors

FOM4 did a good job of overall quantifying the contacts in order from best to worst. Lamtac was superior because of the high current density and low mating force. HBB was penalized for its high mating force but still stood out because it had the lowest resistance per inch and highest current density per inch.

Analyzing these contacts by louver characteristics alone would lead to false conclusions. DW1 had the highest rated current per louver and comparable resistance per louver to that of other contacts. The weakness of the DW1 design was in the large louver spacing required which resulted in less louvers per inch. Thus, it ended up in the middle of the pack in terms of current per inch and third to last in resistance per inch. That, along with a high mating force, resulted in DW1 being ranked low in all FOMs.

A designer could use FOM4 to differentiate between outstanding designs and less versatile designs the contacts of interests could be selected and compared using FOM1, FOM2, or FOM3 based on the priorities of the design at hand. Several contacts could be selected for further investigation to suit the designer's needs.

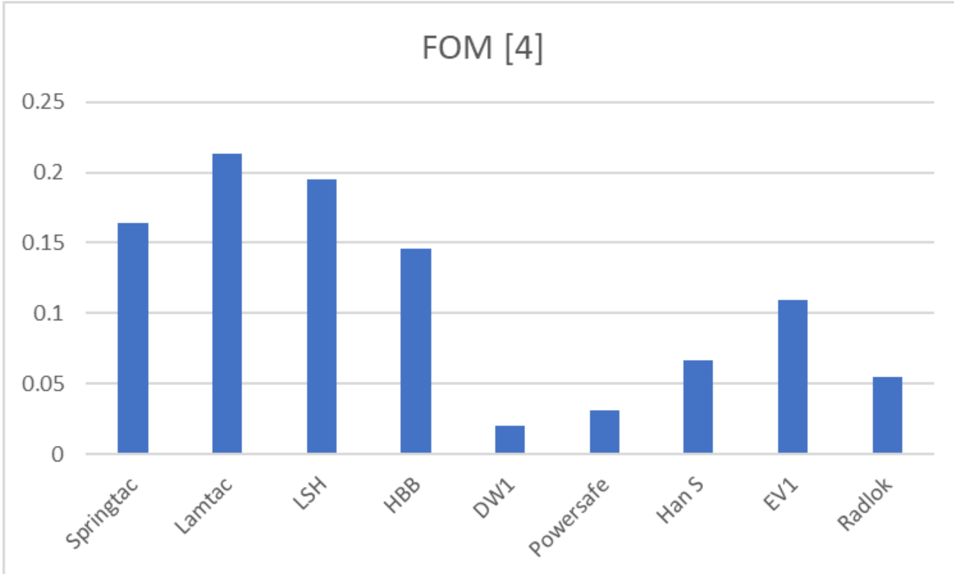


Figure 4-31: FOM4 results for full connectors

The results of the louver only FOMs are graphed in figures Figure 4-32, Figure 4-33, Figure 4-34, and Figure 4-35. The results showed that the Radsok hyperboloid technology rivaled the torsion louver technology. This presented no definitive answer to which electrical contact mechanism was the best. In some cases, Radsok beat out Multilam and in other cases not so much. The FOM graphs show, if all things were equal, the LAIA variety would be the best contact. However, as discussed in 4.1, there were constraints to the LAIA in terms of available diameter size. In these cases, the other Multilams would be better options. There are other factors as well that could factor into selecting a Multilam including misalignment tolerance. These same constraints would need to be considered for the other louver technology presented earlier.

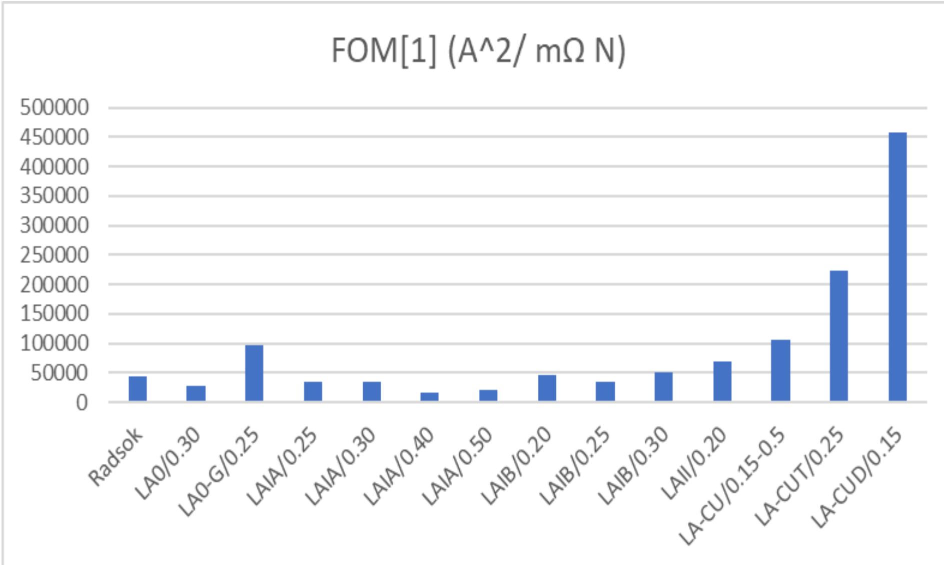


Figure 4-32: FOM1 results for louver only contacts

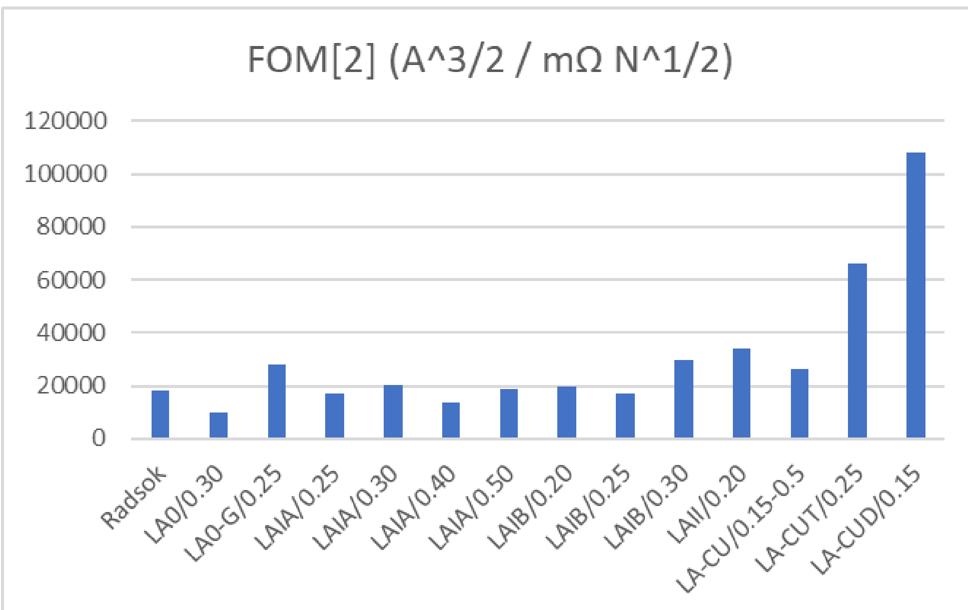


Figure 4-33: FOM2 results for louver only contacts

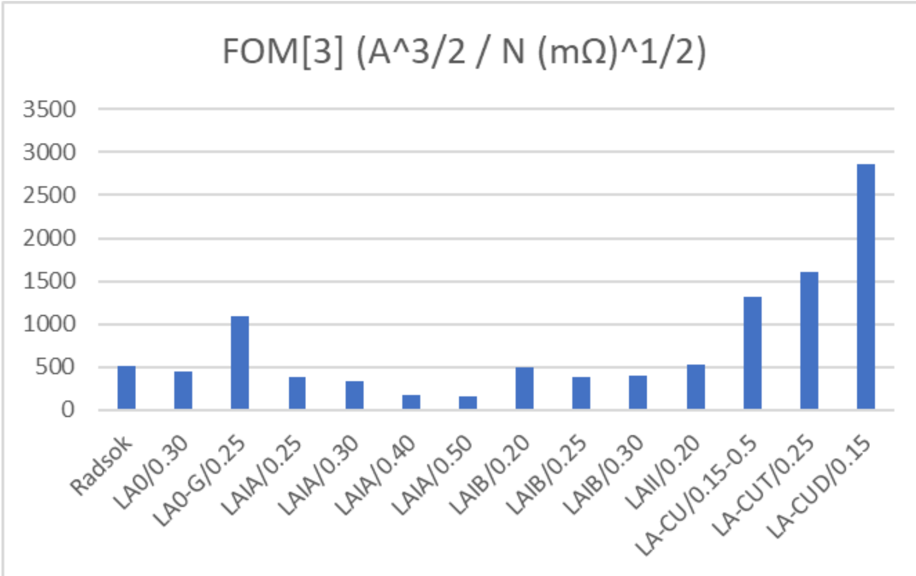


Figure 4-34: FOM3 results for louver only contacts

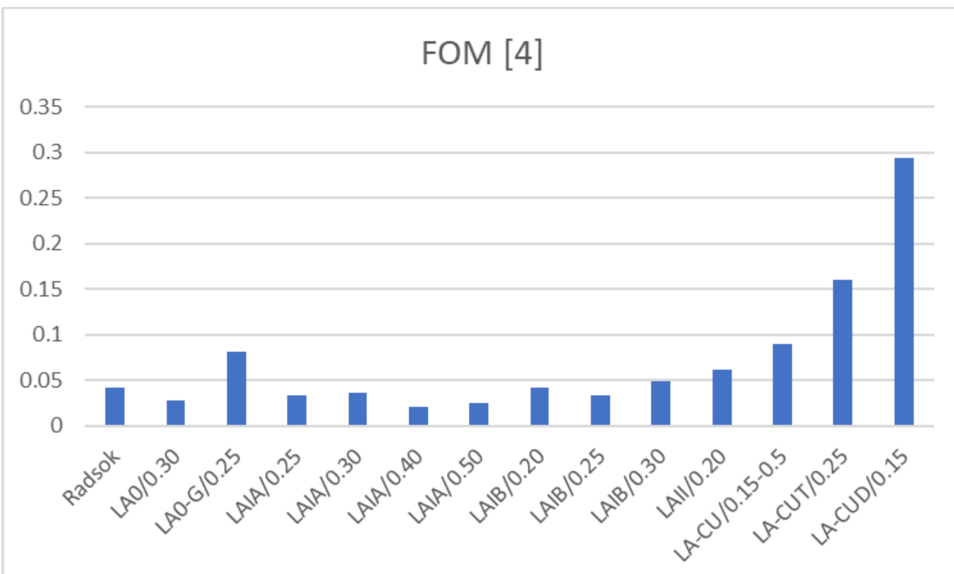


Figure 4-35: FOM4 results for louver only contacts

4.5.4 Figure of Merit and Size

One of the most important aspects of the shipboard connector was keeping it compact. The figures of merit went a long way in identifying good contact candidates. The FOMs were combined graphically with the required size of the contact at a particular current rating in order to make the best design tool when space and compactness were high priorities. The example of comparing connectors at 1000 A is continued in Figure 4-36, Figure 4-37, Figure 4-38, and Figure 4-39. These figures show how size in conjunction with FOM could be used to identify the strengths of the contacts. Full connector results are plotted in blue and louver only contacts are plotted in red. The full connectors and louver only contacts are plotted on the same figures but may only be compared against their own type.

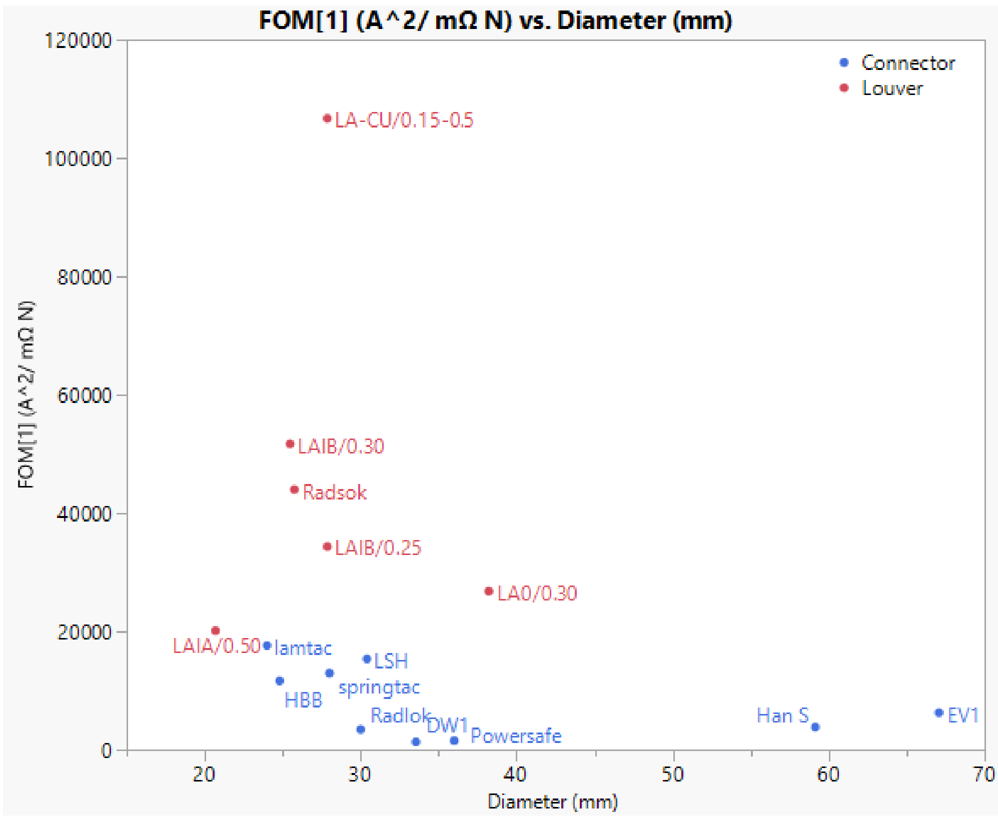


Figure 4-36: FOM1 and size at 1000 A

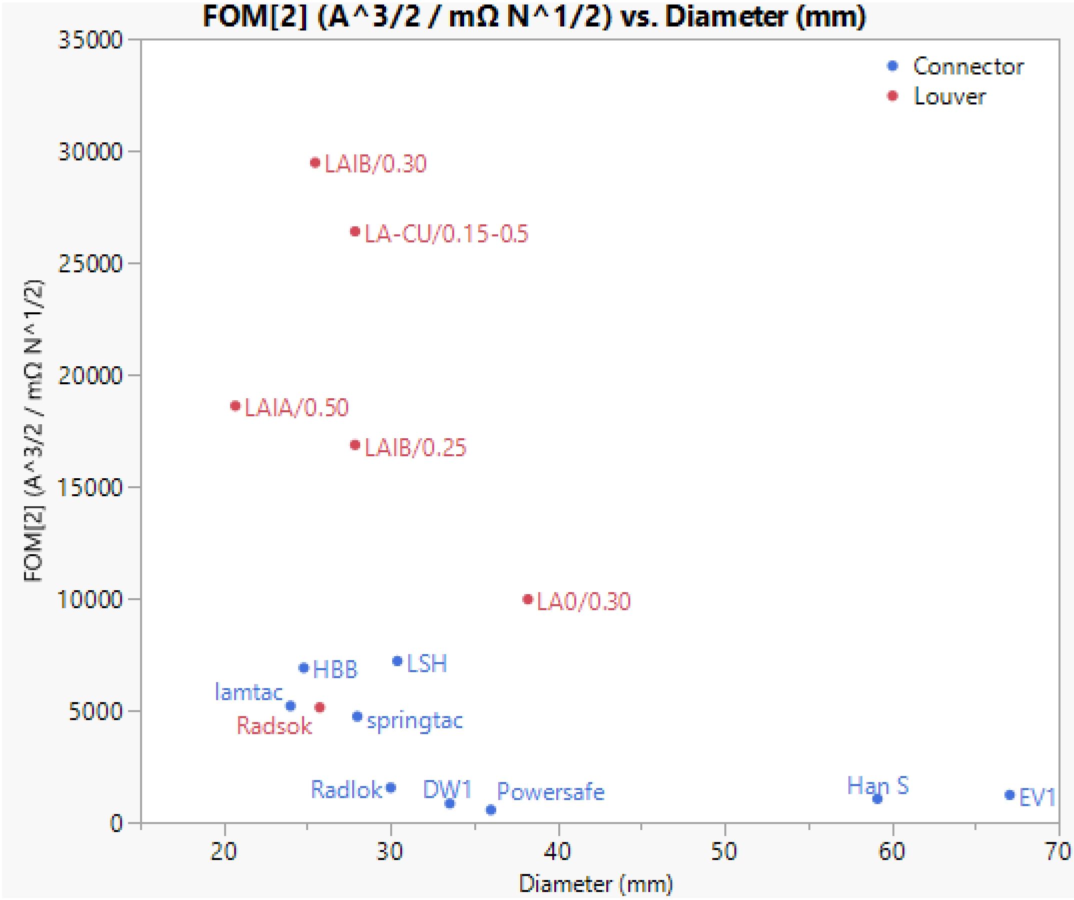


Figure 4-37: FOM2 and size at 1000 A

Since size was an important factor, Han S and EV1 would be ruled out in the design selection process in favor of smaller contacts. FOM alone without size consideration would not be the best way to choose a design. If well scoring contacts on FOM alone were outside of size constraints or twice the size of a contact that had a moderate FOM score, then the choice of choosing a smaller contact was clear through the use of these design graphs. This technique worked best if the contacts were plotted with the FOM and appropriate size for the specific current rating under investigation.

Design graphs and FOMs were only as good as the information available. Only like contacts were compared to each other in this thesis, meaning contacts accounting for bulk resistance could not be compared to contacts accounting for only the louver resistance. Assembled connectors with bulk resistance averaged 7.6 times the resistance per inch compared to louver only contacts. This led to a power dissipation level of 3.5 times higher per inch on average for full connectors compared to louver only contacts. Being able to compare the louver only contacts directly with contacts with bulk resistance either by anticipating the bulk resistance or identifying the only the louver resistance for every louver design would improve the presented contact selection process.

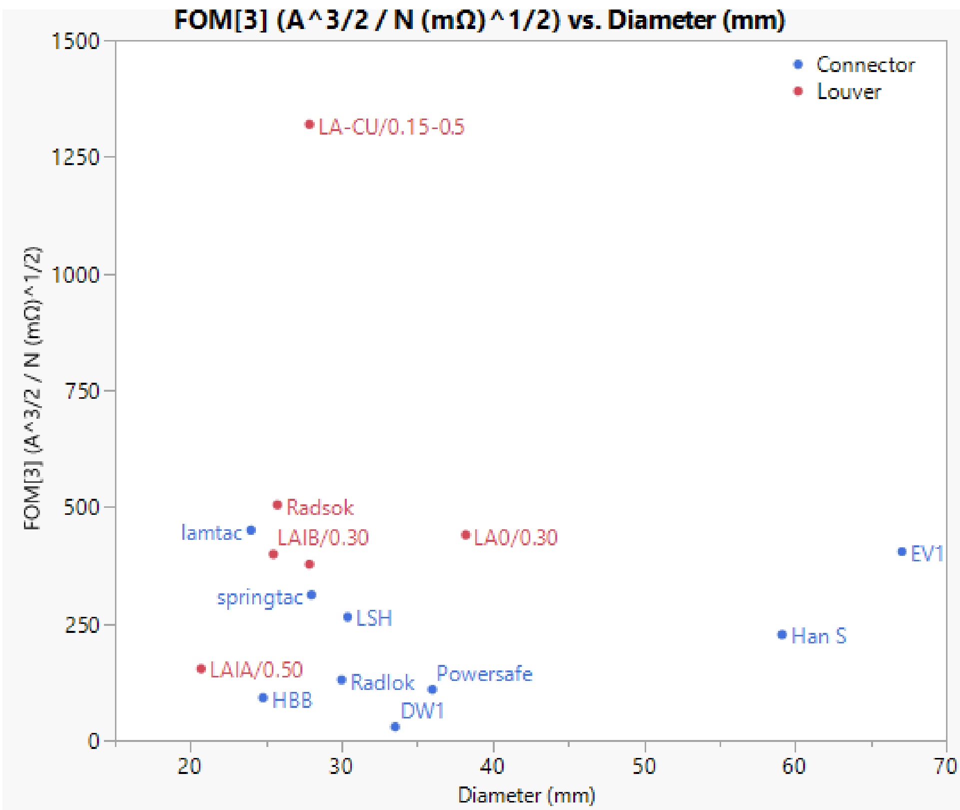


Figure 4-38: FOM3 and size at 1000 A

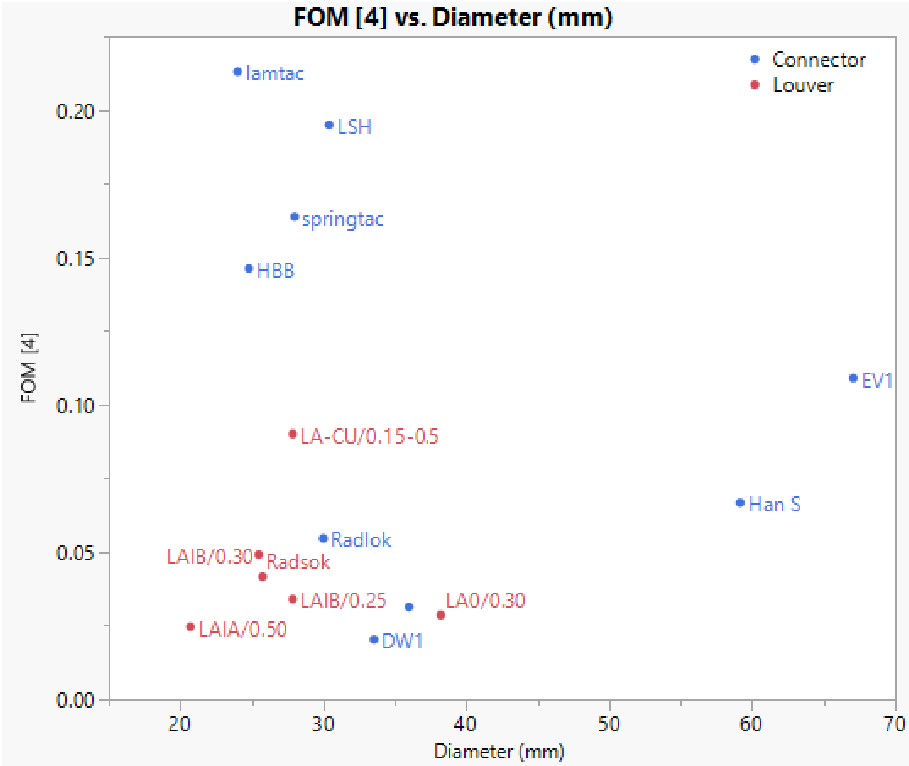


Figure 4-39: FOM4 and size at 1000 A

5 Insulation Parameters

5.1 Creepage Distance

In order to develop the structure of an electrical connector around an electrical contact, the important safety requirement of creepage distance had to be assessed and known. Creepage distance is the shortest distance along the surface of an insulating material between uninsulated electrically conductive surfaces. Figure 5-1 illustrates an example of creepage distance with a rib between two conductive terminals. Creepage distance prevents the phenomena of surface tracking on an insulator. Surface tracking is the formation of carbonized paths along an insulator which eventually grow to a continuous conducting path leading to failure of the connector and risk of electric shock and fire. The danger of failure can be avoided by designing an adequate creepage distance along the insulation of the connector. An adequate creepage distance is influenced by four factors: contamination, moisture, material property of the insulator, and voltage.

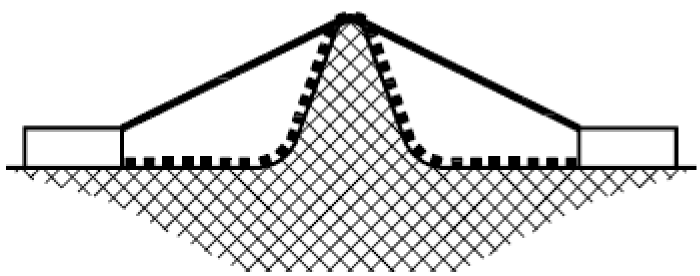


Figure 5-1: Creepage distance in the dotted line illustrated in UL 840 [67]

Contamination and moisture were addressed by determining the connector's ambient operating conditions using the concept of pollution degree defined by the Underwriters Laboratories (UL) standard for safety UL 840 [67]. Pollution degree (PD) was defined by the amount and type of contaminants and condensation or moisture the connector would encounter in its operating micro-climate. The micro-climate was heavily influenced by the macro-environment the connector was a part of, in this case the shipboard environment. The four levels of pollution degree are specifically defined in UL 840.

Table 5-1: Pollution degree as defined by UL 840 and examples from Schau et al [68]

Pollution Degree	Description and example environments
Pollution Degree 1	No pollution or only dry, nonconductive pollution. Indoors, fully air conditioned, dry with no more than average residential dust.
Pollution Degree 2	Normally, only dry nonconductive pollution, however temporary conductivity caused by condensation may be expected. Indoors, in rooms with limited heating or inadequate thermal insulation and, at times, damp. Under certain circumstances condensation may occur. However, such locations are expected to have only an average amount of dust. Examples may be found in apartment house entrances, multi-floor staircases, unmanned telecommunication stations, factories, workshops, storage areas of hardware stores.
Pollution Degree 3	Conductive pollution, or dry nonconductive that becomes conductive through condensation that is expected. In buildings which are unheated or have limited heat capability and inadequate thermal insulation. At times they may be open to outside conditions. Frequent condensation is expected and a considerable amount of dust may be blown about. The area is protected from direct attack by the elements. Examples of these conditions may be found in outdoor telephone booths, barns, vehicles, damp cellars, and enclosed loading docks.
Pollution Degree 4	Pollution that generates persistent conductivity through conductive dust or rain and snow. Unheated building, partly open to prevailing climatic conditions, having long term condensation and large amounts of dust.

Insulators were classified into groups based on their tracking resistance called Comparative Tracking Index (CTI) or Proof Tracking Index (PTI). CTI was used in UL standards and PTI was used in IEC standards. CTI and PTI are essentially the same concept except for the test method employed. CTI testing was conducted using ASTM 3638 [69] and PTI using IEC 60112 [70]. Both tests determined the maximum voltage a material could withstand without tracking in a water contaminated test environment.

The higher the CTI or PTI value the less susceptible to tracking the material was and less creepage distance was required. UL 840, the standard for safety for commercial applications for insulation coordination broke materials into four groups based on their CTI, Table 5-2. In IEC documents the PTI was stated.

Table 5-2: Material groups from UL 840 based on CTI voltage ratings

Material Group	CTI Voltage Rating (V)
I	≥ 600
II	$400 \leq CTI < 600$
IIIa	$175 \leq CTI < 400$
IIIb	$100 \leq CTI < 175$

5.1.1 Creepage Distance Standards

There were several standards that cited a standard for creepage distance based on the above properties. UL 840 was the commercial standard and had the same specified creepage distances as IEC 60664-1, “Insulation coordination for equipment within low-voltage supply systems” [71]. Commercial electrical connectors were designed to IEC 60664-1 according to IEC 61984, “Connectors - Safety Requirements and Tests” [72]. However, the Navy noted in its standard for shipboard electrical equipment, MIL-DTL-917, that the “values in UL 840 tables have been found to be too low for the Navy environment” [73]. MIL-DTL-917F gave its own set of creepage distance standards based on voltage, power rating of the equipment, and whether the equipment was enclosed or open. Per MIL-STD-108E, equipment or parts with no environmental protection and permitted free transmission of air were defined to be open. Equipment had a wide variety of sub categories ranging from drip proof to watertight. Equipment with the suffix “tight” were considered enclosed and were protected by the exclusion of undesirable elements. Equipment with the suffix “proof” were protected from the environment under specific conditions [74].

The standards in MIL-DTL-917 were defined for the “average degree” of enclosure and exposure in the shipboard environment. It advised the designer to “employ creepage and clearance distances in excess of [the] minimums where it [was] probable that structural features, contaminants, lack of maintenance, environment, exposure, or application overstress [would] create service conditions more severe than normal” [73]. The standard also only applied to DC systems equal to or less than 1000 V. It directed users to use IACS (UR) E11 for systems above 1000 V. IACS (UR) E11, “Unified requirements for systems with voltages above 1 kV up to 15 kV” [75]. It in turn directed the user to IEC 60092-503, “Electrical Installation on Ships – Special Features” [76].

IEC 60092 gave creepage distances based on specific PTI insulation ratings and voltage, it did not differentiate between different pollution degrees because it was written specifically for the shipboard environment. It was written for AC distribution systems but there were no other standards that covered the same creepage distance material specifically for DC systems.

The shipboard based medium voltage direct current system employed with the iPEBB and power corridor presented a unique problem when it came to creepage distance. Creepage distance standards for high and medium voltage systems were usually sized for the utility sector whose primary contaminates were dust, rainfall, and fog. That state of contamination was traditionally defined using equivalent salt deposit density (ESDD) but was not applicable to the shipboard environment. The world’s largest vessel classification society, Det Norske Veritas (DNV), provided guidance for dimensioning creepage distances in accordance with IEC 60664-1 and UL 840; use pollution degree 3 and insulation material IIIa [77].

The use of high voltage DC systems in the shipboard contamination setting was an area of study being explored at the time of writing by Damle et al. [63]. Until an updated specific assessment of DC systems operating in the shipboard pollution environment can be accomplished and standards updated to reflect the results, the MIL-DTL-917, UL 840, and IEC60092 were the guidelines to which to design shipboard electrical equipment. Navy standards were presented in step functions, therefore at the high and low ranges of those steps it was difficult to directly optimally design creepage distance through the Navy standards alone.

The applicable creepage distance path that the high-power shipboard connector design needed to be concerned with was defined by IEC 61984 in its differentiation between a plug and a connector. The creepage distance of a connector without breaking capacity, one that would not be engaged or disengaged when live or under load, was only measured in the mated condition. A plug on the other hand could be connected under differentiating potential and no current and its female part in the unmated condition needed to conform to creepage distance standards as well. The shipboard connector did not have breaking capacity and could not be disconnected without deenergizing the circuit of both current and voltage. Therefore, the high-power shipboard connector only needed to pass creepage standards in the mated condition.

The UL 840 standard was compared to the military standard in Figure 5-2. The military standard was stricter when it came to higher power electrical equipment. There was some overlap and comparable creepage distance requirements between military equipment between 50-2000 W and UL pollution degree 3 material IIIa. However, military equipment with power above 2000 W always required more creepage distance than UL 840 standards for pollution degree 3. Open military equipment required minimum creepage distance to always be above any UL 840 standard. Above 600 V the military standard far exceeded the commercial standard.

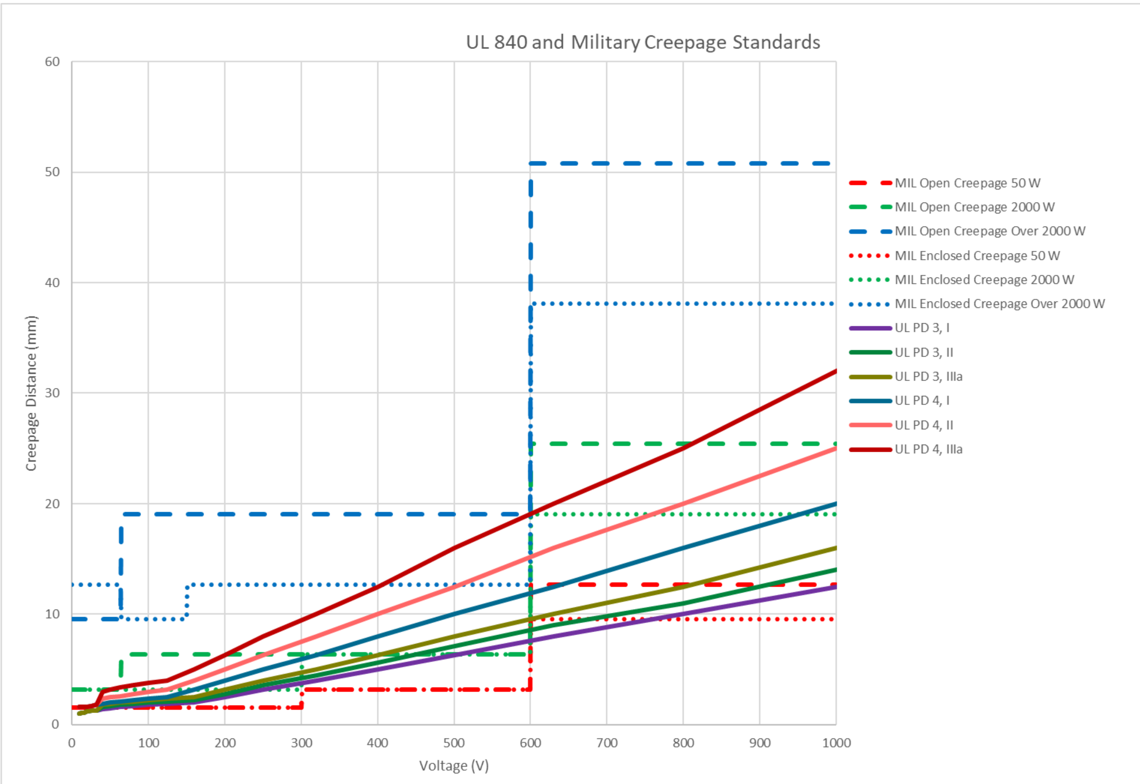


Figure 5-2: MIL-DTL-917 creepage distance compared to UL 840 creepage distance from 0-1000 V

Above 1000 V IEC 60092 took over as the military standard. IEC 60092 like the lower military standard was written as a step function, a specific creepage distance covered a wide voltage range. It was not a clean handoff between the MIL-DTL-917 creepage distance at 1000 V, as shown in Figure 5-3, and the IEC standard. The IEC standard was split between creepage distances for switchboard equipment and creepage distances for equipment outside of the switchboard. The switchboard creepage distance requirements were more conservative than the "Other" equipment category. The IEC standard did not differentiate between pollution environments as it is written entirely for the shipboard environment. IEC 60092 like UL 840 was broken down between material groups for tracking tolerance. Material group IIIa from UL 840 corresponds to the 300V PTI tracking tolerance in IEC 60092.

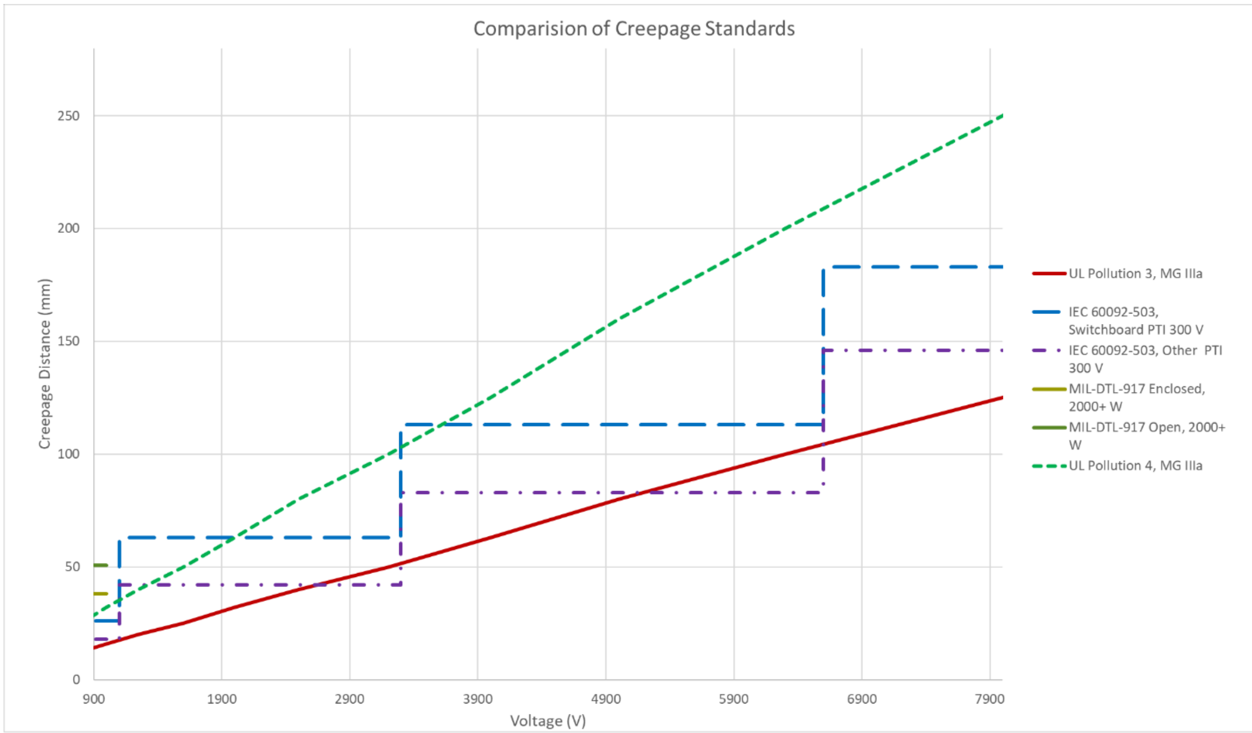


Figure 5-3: Graphical comparison of creepage distance standards 900 – 8000 V

The IEC switchboard creepage standard was always higher than UL 840 pollution 3. The IEC "Other" creepage standard however intersected with the UL 840 pollution 3 requirement in each of its steps. At the lower end of the voltage range covered by the voltage step, IEC was more conservative, and at the higher range of the voltage step UL 840 was more conservative. The most conservative of all was UL 840 pollution degree 4. After crossing the IEC switchboard step function a few times below 3600 V it always required the greatest creepage distance at higher voltages.

Based on designing according to the DNV recommendation pollution degree 3 and material group IIIa, as well as understanding the military's statement on finding UL standards generally too low, the best starting point for a shipboard military design was to follow IEC 60092 switchboard PTI 300 V creepage distance requirements. That standard should be used as a starting point for a shipboard military design. Additional review of the specific environmental shipboard conditions could lead to increasing or decreasing the creepage distance.

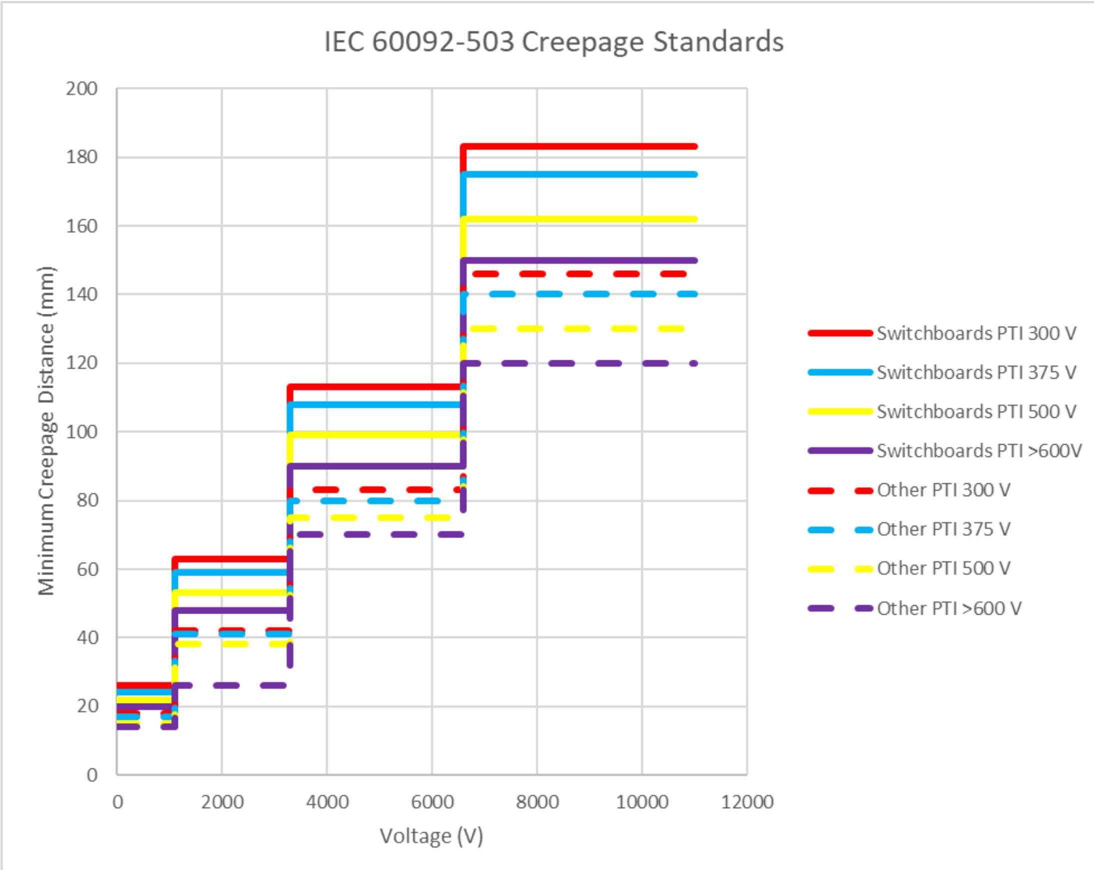


Figure 5-4: IEC 60092 Creepage Distances

Figure 5-4 shows the IEC 60092 standard across all PTI categories for switchboard and non-switchboard equipment. The most tracking resistant switchboard material always required a greater creepage distance than the least tracking resistant insulator in non-switchboard equipment.

5.1.2 Survey of off the shelf Connector Creepage Distances

Besides standards, an empirical survey of existing connectors to gain insight on the state of the practice was made. The mated creepage distance of twenty-one connectors of various voltage, current, power, environmental application, material, and IP ratings were measured either from engineering drawings or measured on sample connectors. Upon review of the information three trendlines were pulled from the data. The first was the mated creepage distance as a function of operating voltage using a linear fit for all surveyed connectors. The data was then split between “High Creepage” connectors and “Low Creepage” connectors based on if they fell above or below the first linear all-data trendline. A linear trendline was then fit for each set of data (high and low).

The results are displayed in Figure 5-5. Figure 5-6 shows the specific surveyed connectors with their corresponding creepage distance, voltage rating, and application.

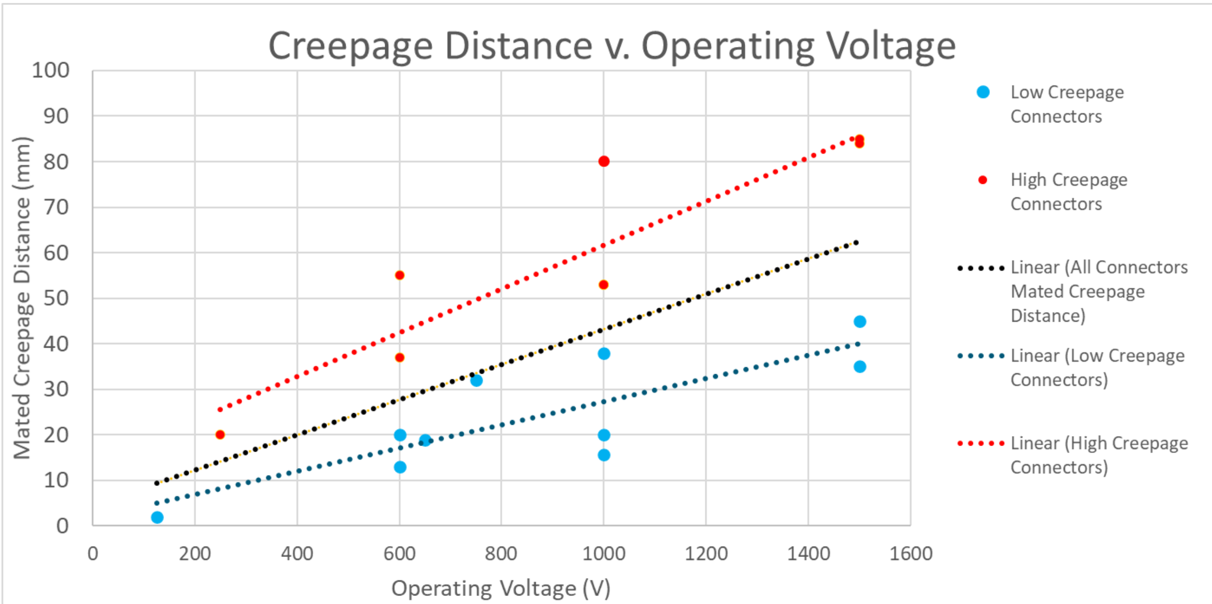


Figure 5-5: Linear trendlines based on creepage distances on surveyed connectors

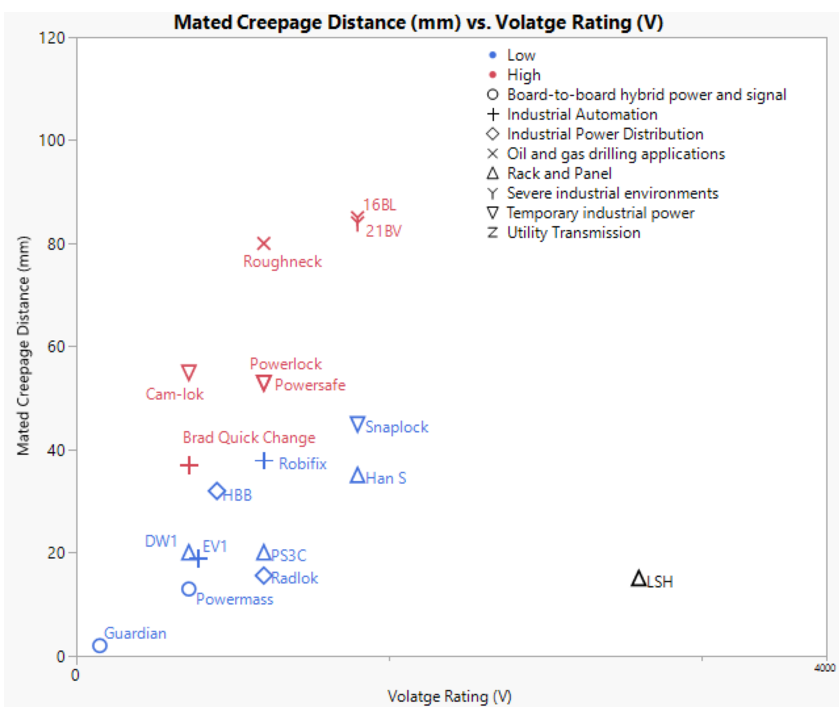


Figure 5-6: Creepage distance of surveyed connectors

Table 5-3 displays the corresponding pollution degree for a given connector application. In an effort to consolidate the number of applications the connectors were grouped into eight categories. In a specific category, the pollution degree may vary between two categories due to some connectors being built to a higher expectation of contamination in its application. It was clear that applications with less severe environmental conditions had less creepage distance incorporated into the connector design consistent with standards reviewed in 5.1.1.

One-thousand-volt connectors for instance had a variety of creepage distances. The Radlok and PS3C generally were used as rack and panel connectors or for power distribution, which had a closer pollution environment to that of PD 2; a factory or power distribution space never exposed to the outside environment and always temperature controlled. Robifix was a more robust connector designed to be on the factory floor providing power to welding machines, a micro-climate of PD 3. At the same voltage, Powerlock and Powersafe were exposed to the outside environment, PD 4, and roughneck was built to be routinely exposed the muddy environment near oil drilling rigs. Creepage distance was increased on connectors operating in a higher PD.

The "High Creepage" connector designs were made to be exposed to environments in PD 3 or 4. Of the eleven connector that made up the "Low Creepage" connectors, four were built to encounter pollution degree 3 and all others were made with the expectation of PD 1 or 2.

Table 5-3: Connector application and corresponding pollution degree

Application	Pollution Degree for entire connector
Temporary industrial power	4
Severe industrial environments	4
Oil and gas drilling applications	4
Utility Transmission	4
Industrial Automation	2 or 3
Industrial Power Distribution	2 or 3
Rack and Panel	2
Board-to-board hybrid power and signal	1 or 2

Two outlier connectors were identified, LSH and Loadbreak. These connectors stood out as they did not conform to standards and had particularly small creepage distances for their operating voltages. The reasoning behind the creepage distance was not explicitly known, but it illustrates the possibility of precise engineering where the micro-environment and insulation material was well understood. With proper testing of the design, it could have proved unnecessary to increase creepage distance for these connectors and their applications. The Loadbreak elbow for example was a common utility connector and dimensionally regulated by the same societies that put out creepage standards [78]. These two connectors *were not* used in the calculation of the trendlines.

The total power of the connectors was plotted in Figure 5-7 to find trends between application, power, and creepage distance. Although power was only taken into account in the military standard, a clear correlation between the power the connector was designed to carry and the creepage distance was demonstrated in Figure 5-7. The majority of the “High Creepage” connectors were above 400 kW. The two outlier connectors moved closer to the center of a linear regression for all connectors as seen in Figure 5-8.

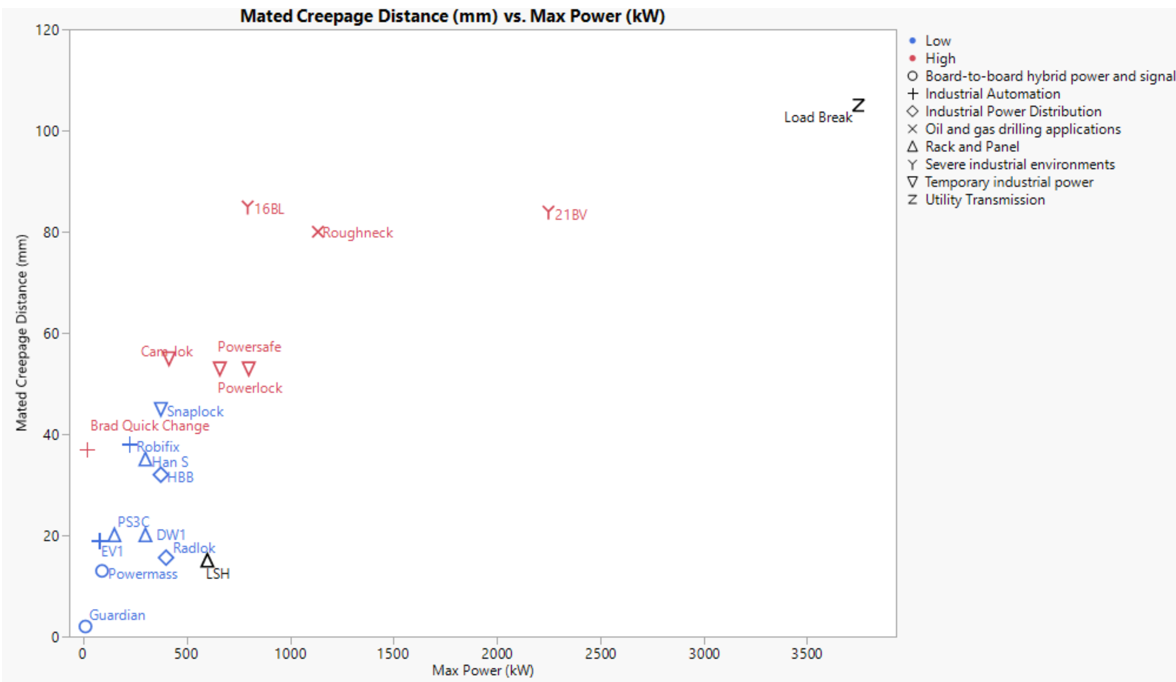


Figure 5-7: Creepage distance in relation to power of surveyed connectors

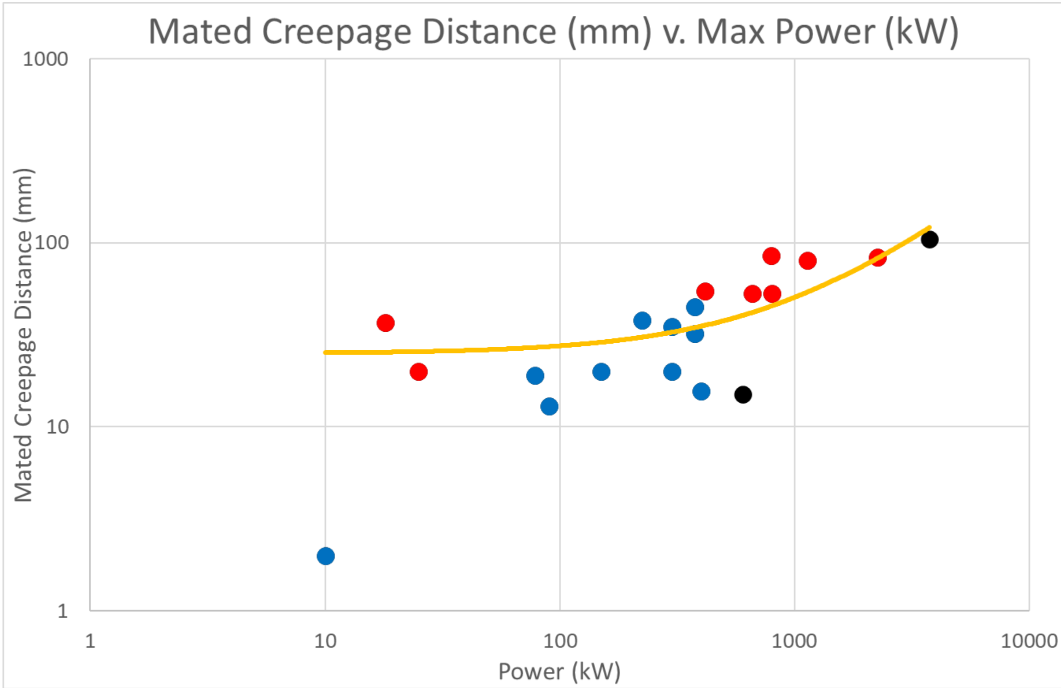


Figure 5-8: Log-Log plot of creepage distance and max power of surveyed connectors with a linear fitted trend line

The last part of the empirical connector survey involved the Ingress Protection rating, as described in chapter 2.4, and the effect on creepage distance. The standard for connector safety, IEC 61984, stated that insulating parts inside an enclosure with IP protection of IP54 or higher, may be sized for a lower pollution degree. This might be a factor in how the Loadbreak was able to decrease its creepage distance, the outer weather protection could have allowed for insulation to be sized for a lower micro-environment. Figure 5-9 shows the connectors surveyed with known IP protection ratings. It appeared that some products may have taken advantage of the IP rating to lower creepage paths. Powerlock and Powersafe, which operated at a higher voltage but had a higher protection rating, IP67, had a lower creepage distance than the Cam-lok which had a low IP14 rating.

Through comparison of connectors at the same voltage, it was clear that creepage distance grew with a higher IP rating. At 1500 V, the Han S had the shortest creepage distance and the lowest IP rating while 16BL and 21BV had the highest IP rating but also the longest creepage path. The higher IP rating was necessary due to the environment the connector was to work in, severe industrial conditions versus rack and panel conditions. The increase in pollution degree due to the environment also necessitated a longer creepage distance and a higher IP rating. The IP rating also influenced the mechanism to keep the connector water and dust protected. The more robust the protection the larger the connector tended to be and an increase in the creepage path tended to grow naturally as a result.

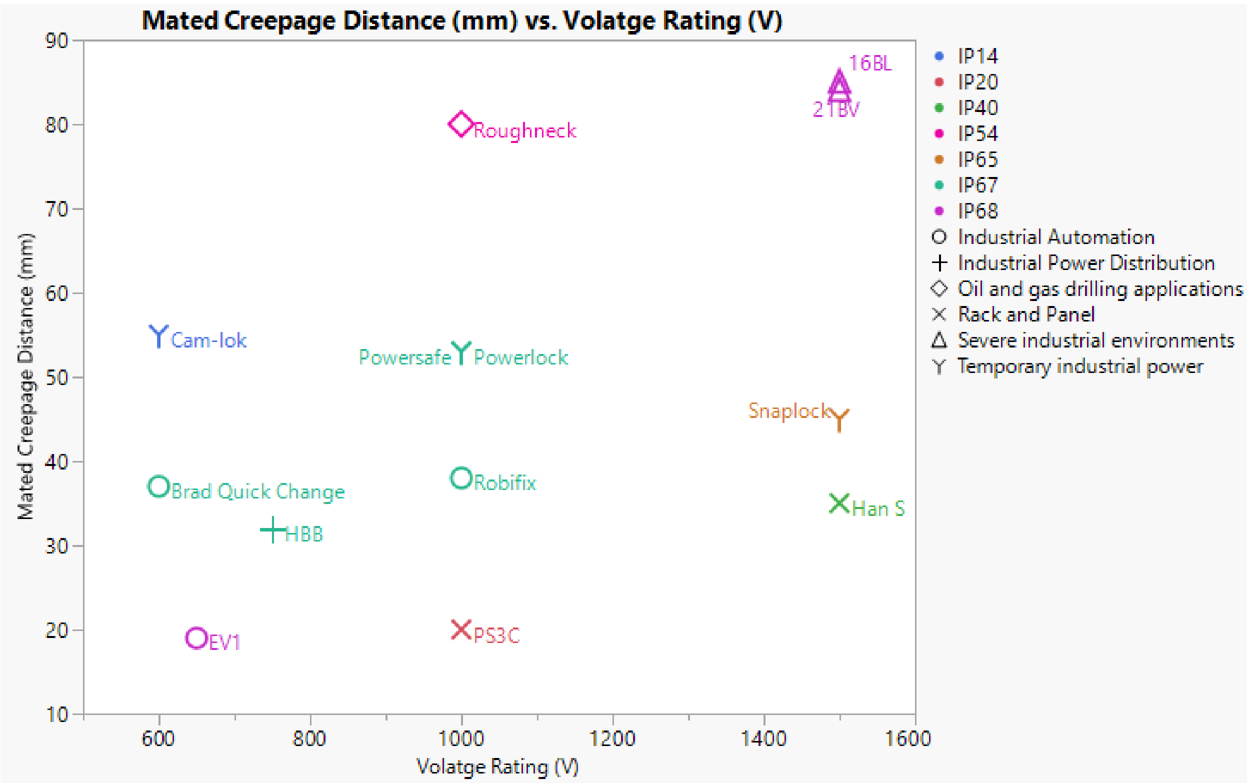


Figure 5-9: IP rating and creepage distance of surveyed connectors

Another source of empirical data came from a paper from 1985 entitled "Survey of Creepage Distances and Clearances in HVDC Converter Stations". The paper presented the results of a survey of creepage distance for indoor and outdoor insulators at 29 separate DC convertor stations [79]. The results of the survey produced a common range of creepage distance per kilovolt, for indoor applications 1.4-2.6 cm/kV and 2.4-5.1 cm/kV for outdoor applications. This information was used to create six design lines, three for indoor and three for outdoor insulators. The lines were made by taking the lower end of the range, the middle of the range, and the upper end of the range of creepage distance per kilovolt. The results are in Figure 5-10.

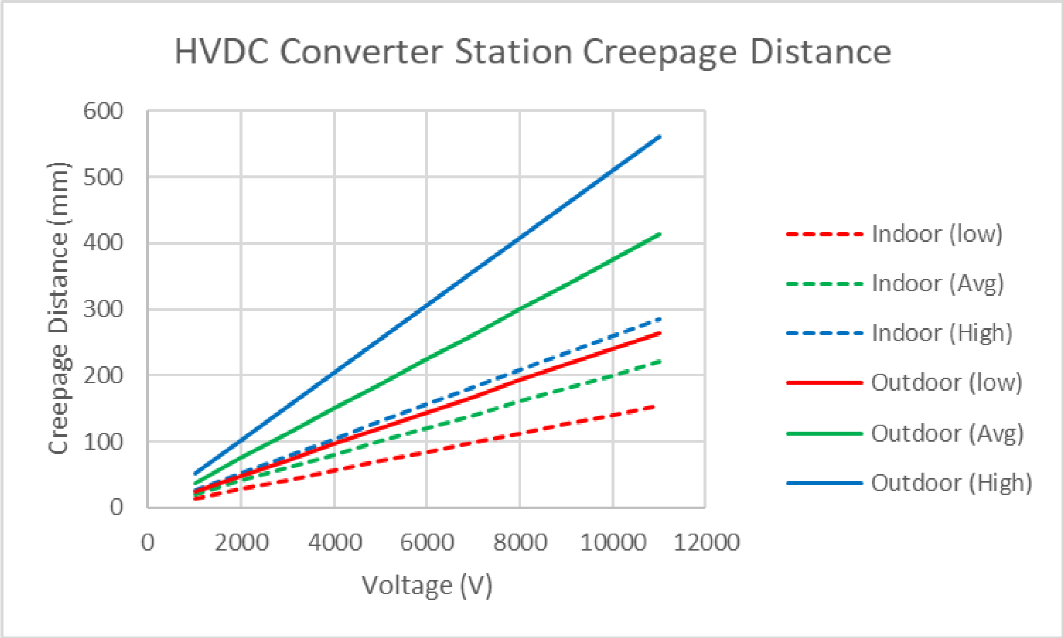


Figure 5-10: Creepage distance design lines based on a HVDC converter station survey by Ong

5.1.3 Comparison between standards and surveys

5.1.3.1 Less than or equal to 1000 V connectors

The military standard presented options for three power ranges. Only the military standard for 2000 W and up electrical equipment is presented in this section considering the high-power shipboard connector was always to be designed for a higher power rating than 2 kW. All surveyed connectors were rated for above 2 kW of power.

The surveyed connectors are plotted against the UL 840 and military standards in Figure 5-11. Seven of the nine “Low Creepage” connectors fell on or near UL 840 standards for the rated voltage. Two connectors (Powermass, Robifix), landed very near the military standard for enclosed equipment and one (DW1) met the open equipment standard. All of the “High Creepage” connectors met or exceed the military standard for open equipment.

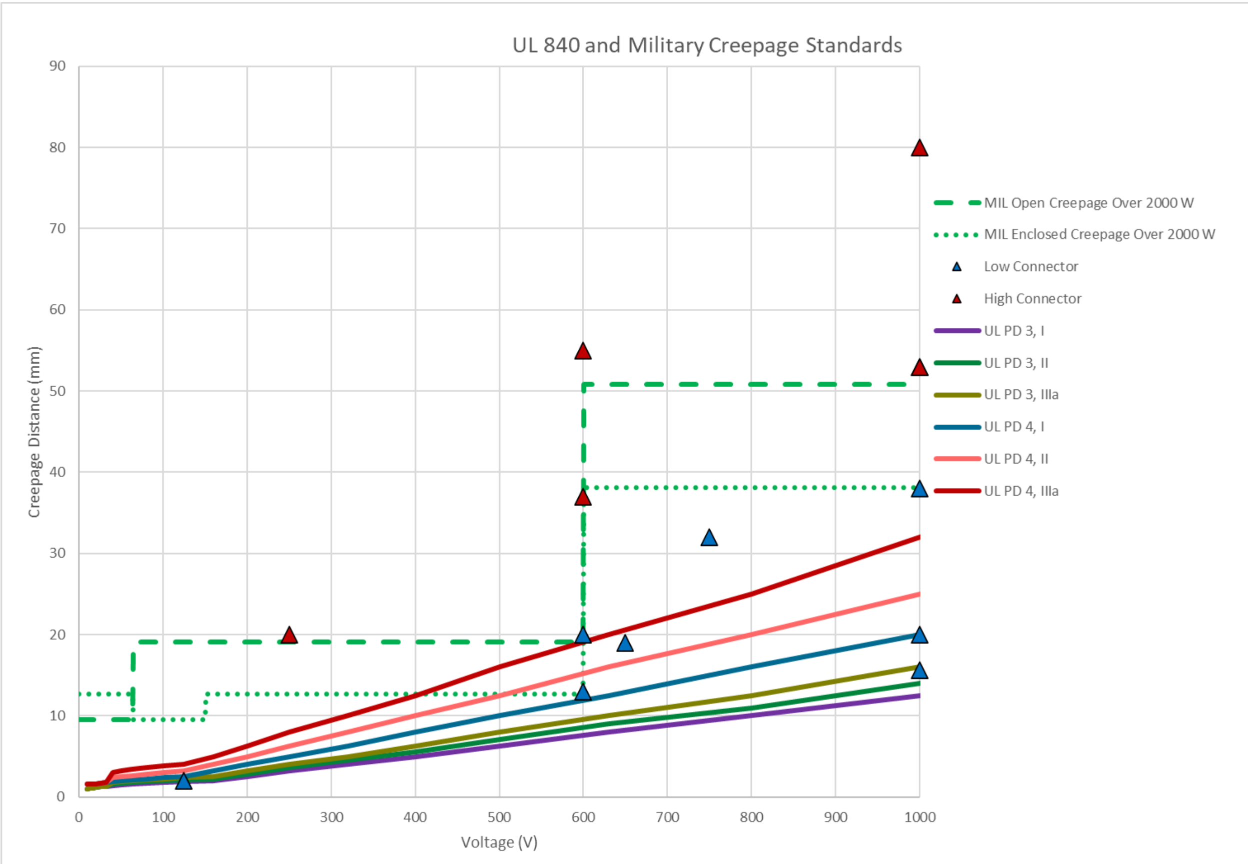


Figure 5-11: Surveyed connector creepage distances compared to standards

The resulting trendlines from the surveyed connectors in 5.2 are shown in Figure 5-12. The Low Creepage line was similar to the UL 840 pollution degree 4 standard. The all-connector average line did not always meet military standards. The high creepage average line always exceeded the enclosed standard and presented a good trend for design of creepage distance outside of 600-800 V.

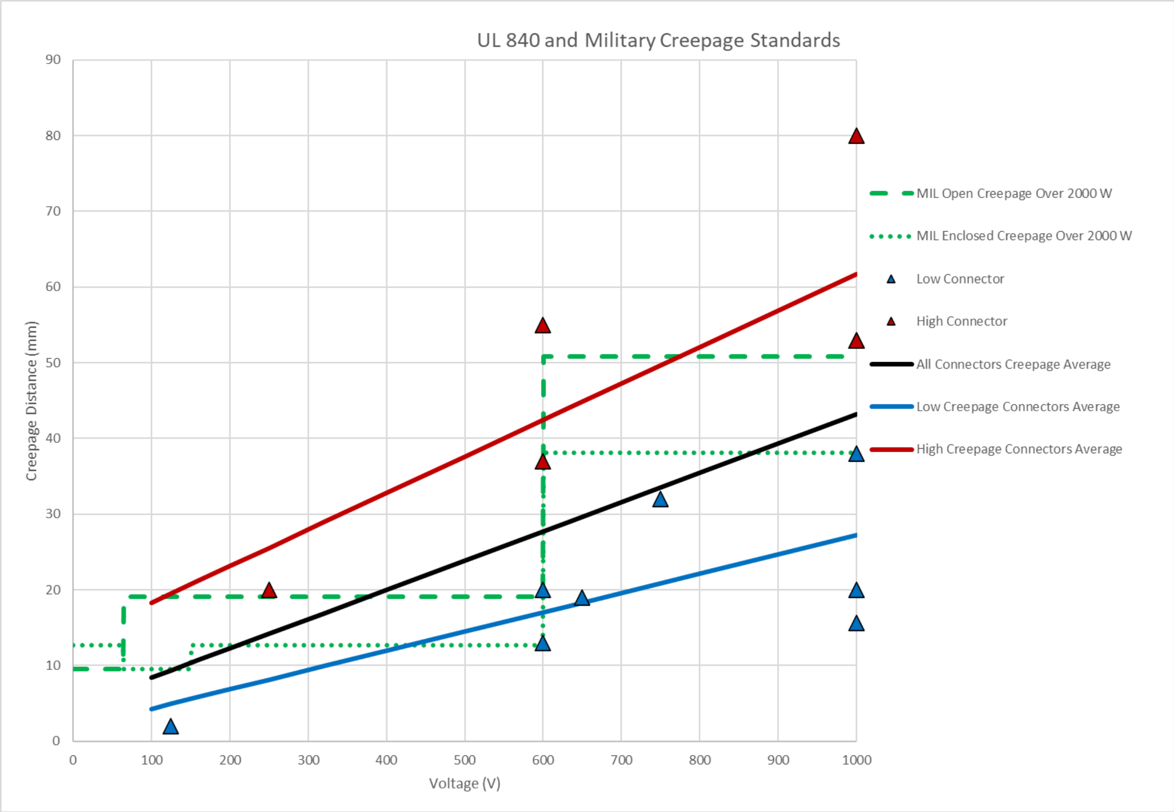


Figure 5-12: Surveyed connector creepage distances compared to survey trendlines

5.1.3.2 Above 1000 V Insulation

A comparison between the HVDC survey and UL 840 standards revealed that the low indoor line from the HVDC survey lined up with the UL 840 pollution 3 material group II standard and the indoor average HVDC lined up with the UL 840 pollution 4, material group I standard, as seen in Figure 5-13. The UL 840 pollution 4, material group II standard straddled the outdoor low and indoor high survey results. The outdoor average and high HVDC survey lines exceed any UL 840 standard. With these results in mind, they could be compared to the IEC standard and conducted connector survey.

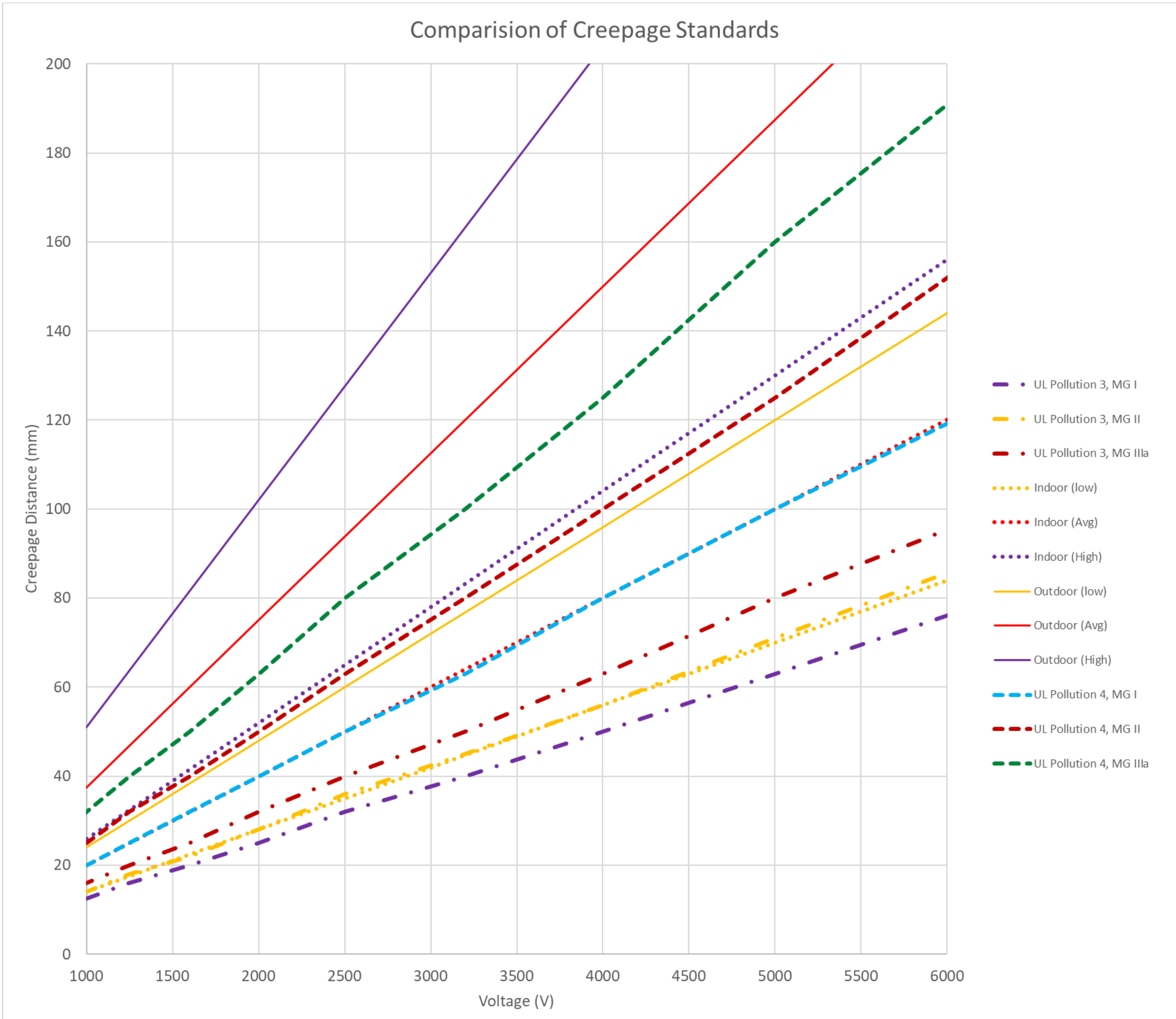


Figure 5-13: Comparison between HVDC survey creepage design lines and UL 840 creepage distance standard

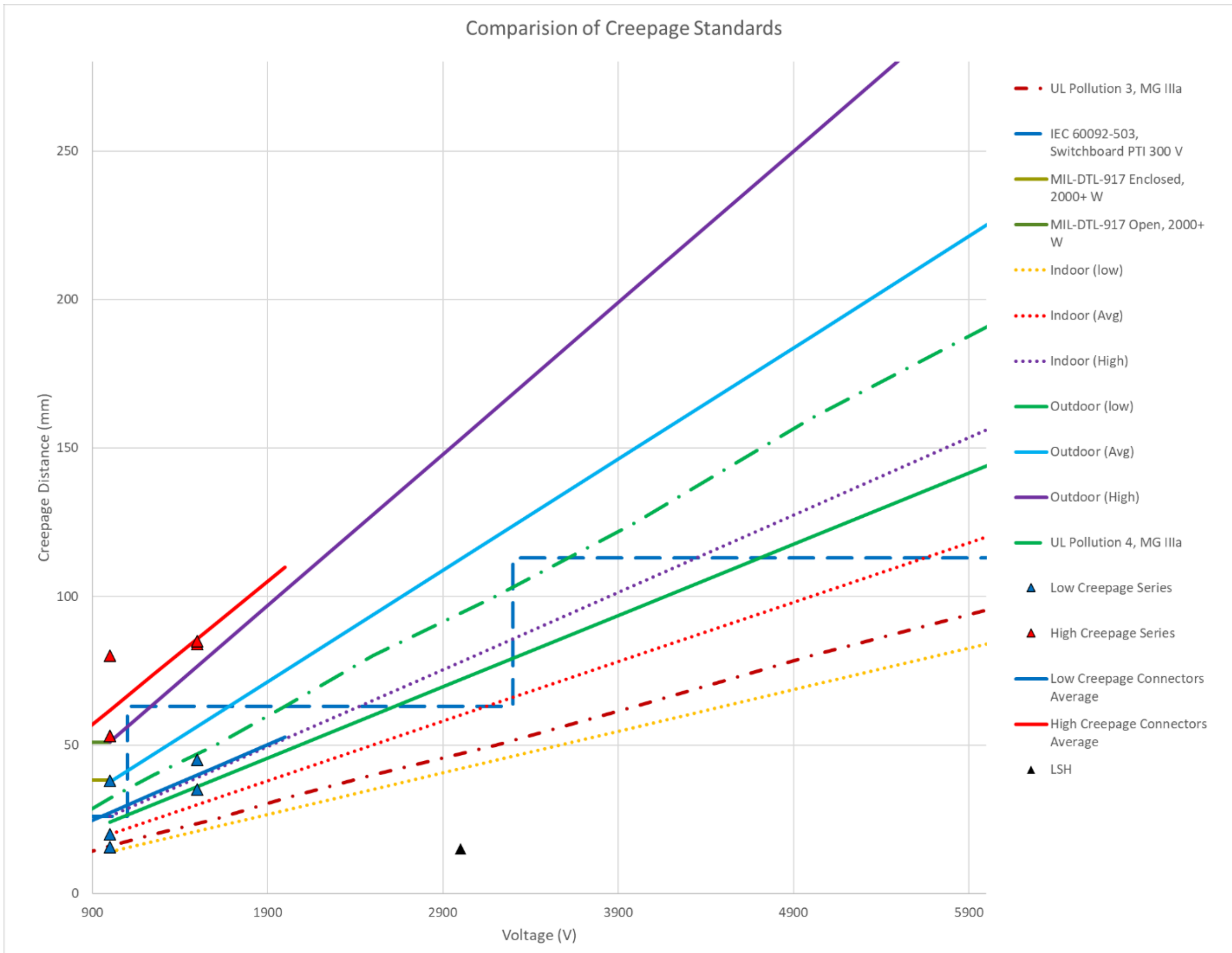


Figure 5-14: Comparison between surveyed connectors, HVDC survey creepage design lines, and selected UL and IEC creepage distance standards

Figure 5-14 shows the surveyed connectors rated 1000-6000 V, the created trendlines up to 2000 V (they weren't extended beyond that since there was no connector data incorporated into them above 1500 V), the lines created from the HVDC survey, and the UL and IEC standards discussed in 5.1. The low creepage connectors fell just above the UL standard. The connector survey trendlines ended up following very closely to the High Indoor insulator creepage distance from the HVDC survey. The high creepage connectors were all above any standard or any HVDC survey line and resulting trendline almost paralleled the High Outdoor insulator creepage distance from the HVDC survey. The High Outdoor HVDC survey line appeared to be too conservative for the shipboard environment for which IEC 60092 was written. The high creepage connectors were also all made with high IP protection in anticipation of working in the severe environmental conditions. With this in mind Figure 5-15 reflects a more pared down graph of useful design lines.

IEC 60092 was the military standard and should be adhered to above 1000 V, but because it was a step function, near the upper end of the voltage range of the step there was room to justify designing in additional creepage distance. Considering the disparity between switchboard and non-switchboard equipment creepage distance requirements, the additional standards and common practice lines are useful to the designer. Designs should account for the wide range of creepage distances and try to incorporate a flexible aspect into the design as testing and future work on the Navy shipboard specific environment may reveal a more defined window for insulator creepage distance design.

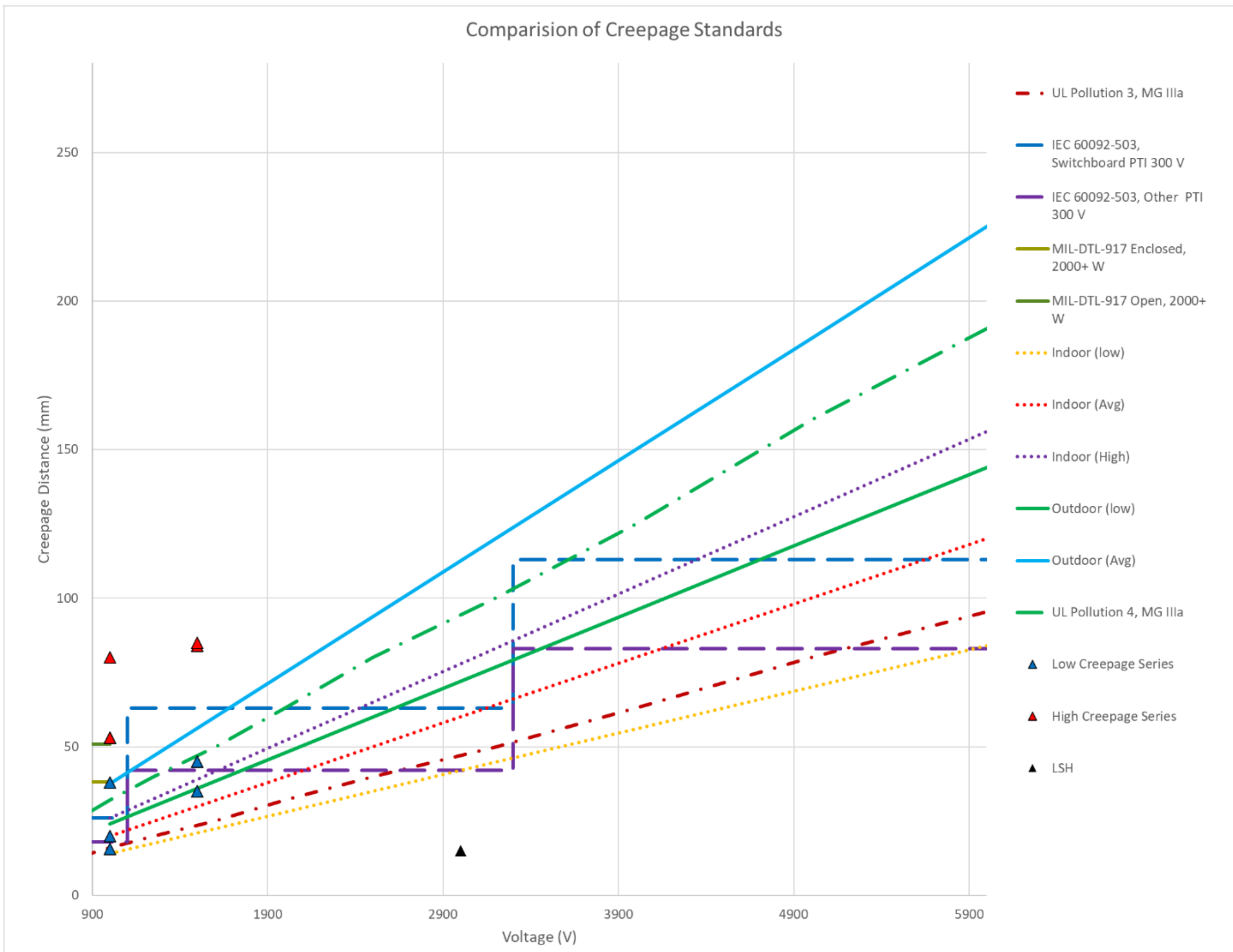


Figure 5-15: The most applicable standards and creepage distance survey trendlines above 1000 V

5.2 Shipboard Environmental Parameters and Protection

The shipboard environment required careful consideration when detailing the atmospheric and micro-climate conditions an electronic piece of equipment would face. Different parts of a ship had very different temperature and moisture exposure. Electronics in the pilot house may be exposed to the elements at times when the doors are open and could experience the widest range of temperature based solely on the outside temperature of the ship. Electrical equipment in electronics specific space however, may always be under air-conditioned controlled temperature air flow. Equipment must be designed appropriately to the area of the ship it will be placed in service. DNV and the American Bureau of Shipping (ABS), the American classification shipping society, published guidelines for design conditions for electrical equipment based on location, Table 5-4.

Table 5-4: Ambient design conditions based on location of equipment on a ship per DNV [77] and ABS [80]

Environmental area	Parameters	Design Conditions
Entrance to the ship/ for design of heating/ cooling systems	Air temperature	-15 C to +35 C
	Max. Heat content of the air	100 kJ/kg
	Seawater temperature	-2 C to +32 C
Inside the ship/ all spaces	Air temperature	0 C to 45 C
	Atmospheric pressure	1000 mbar
	Max. relative humidity	up to 100 % (+45 C)
	Salt content	1 mg/m^3
	Oil vapor	withstand
	Condensation	to be considered
Inside the ship/ air-conditioned area	Air temperature	0 C to 40 C
	Max. relative humidity	100 %
	Recommended ideal climate for manned computer spaces	air temperature +20 C to +22 C at 60% rel. humidity
Inside the ship/in electrical devices with higher degree of heat dissipation	Air temperature	0 C to +55 C
	Max. relative humidity	100 %

The other aspect of electrical design that changed drastically in different parts of the ship was ingress protection. Again, the international classification societies gave guidance based on the location of the electrical equipment and type of equipment. The full consolidated table is in Appendix C. Table 5-5 shows the applicable protections for possible locations and classifications for the high-power shipboard connector under 1000 V and Table 5-6 the protections for the high-power shipboard connector greater than 1000 V.

Table 5-5: Applicable IP protections of electric equipment below 1000 V based on shipboard location

Condition in location	Example of location	Switchboard, control gear, motor starters	Transformers	Socket outlets	Accessories (e.g. switches, connection boxes)
Danger of touching live parts only	Dry accommodation spaces, dry control rooms	IP 20	IP20	IP20	IP20
Danger of dripping liquid and/or moderate mechanical damage	Control rooms, wheel-house, radio room	IP22	IP22	IP22	IP22
	Engine and boiler rooms above floor	IP22	IP22	IP44	IP44

Table 5-6: Applicable IP protections of electric equipment above 1000 V based on shipboard location

Condition in location	Example of location	Switchboards, Distribution Boards, Motor Control Centers and Controller	Transformers, Converters	Electrical Machinery Terminal, Junction, Connection Boxes
Danger of touching live parts only	Dry control rooms Authorized Personnel Only	IP32	IP23	IP44
	Dry Control Rooms	IP42	IP44	IP44
Danger of dripping liquid and/or moderate mechanical damage	Control rooms Authorized Personnel Only	IP32	IP23	IP44
	Control Rooms	IP42	IP44	IP44
	Above floor plates in machinery spaces Authorized Personnel Only	IP32	IP23	IP44
	Above floor plates in machinery spaces	IP42	IP44	IP44

The exact location of the high-power electrical connector on future ships was unknown. The tables summarized the likely places the connectors would be utilized corresponding to likely systems. Connectors operating under 1000 V required a rating of IP20, but there had to be absolute certainty there was no dripping liquid including condensation in the space. Connectors rated above 1000 V required a solid object protection rating of 4 unless the connector could only be accessed by authorized personnel. Water protection varied based on the definition of the connector's equipment system.

The definition of dry and wet spaces was important to understand Table 5-6 and Appendix C. Dry operating spaces were spaces in which no moisture normally occurred (e.g. engine control rooms, operation command centers) and there were measures against condensation under normal operation [80]. An example of a "Dry control room," was explained in the ABS standard as a space where "the equipment [was] located as to preclude being exposed to steam, or dripping/spraying liquids emanating from pipe flanges, valves, ventilation ducts and outlets, etc., installed in its vicinity, and the equipment [was] placed to preclude the possibility of being exposed to sea or rain" [80]. Wet operating spaces were spaces in which facilities may be exposed to moisture (e.g. main engine rooms) [77].

5.3 Navy and shipboard specific insulation parameters

Outside of creepage distance, there were other insulation properties and requirements that had to be met in order to make a safe shipboard electrical connector. Existing military electrical connectors and plug-in sockets were listed in the military standard MIL-STD-1353 [81]. The standard specifies further applicable detail specification documentation detailing the requirements and testing associated with each connector. There were no connectors similar to the high-power shipboard connector in terms of carrying high current, voltage, and power in a single pole compact connector in the shipboard environment. Therefore, no one existing connector could be used as a guide to detail the required insulation characteristics and tests. More general documents needed to be found in order to guide parameter setting for the new connector.

The military standard MIL-DTL-917 was the most useful guide for setting insulation and connector parameters. It covered the basic requirements applicable to the design, material, and construction of naval shipboard electric power equipment. This standard gave insulation specific requirements that the high-power electrical connector would have to meet, specified in Table 5-7

[73]. The standard also detailed the flammability requirements of the insulation material, Table 5-8.

Table 5-7: Insulation design parameters defined by MIL-STD-917

Parameter	Design Condition
Insulation Resistance	> 10 megohms at 77ºF
Dielectric Withstand Voltage	Twice the rated voltage of the circuit plus 1000 V
Arc Resistance (<2000 V)	130 sec. minimum
Tracking resistance (<2000V)	70 minutes minimum
Arc Resistance (>2000 V)	150 sec. minimum
Tracking resistance (>2000V)	300 minutes minimum

Table 5-8: Flammability design parameters defined by MIL-STD-917

Flammability Limit
Ignition: 95 sec. minimum
Burning: 120 sec max.
Weight loss: 15% max. Ratio
Burning time: 10 sec. max.
Extent of burning: 25 mm max.

The dielectric withstand voltage was important when it came to selecting an insulation material. The dielectric strength of a material was the minimum applied electric field that resulted in the breakdown of the insulator at which point it became electrically conductive. Dielectric strength was influenced by several factors including the temperature, mechanical loading, and fabrication process of the insulator. Temperature had an inversely proportional effect; material dielectric strength usually decreased with an increase in temperature. Mechanical stresses introduced internal flaws leading to leaking paths through the material. Paths could also be a product of the formation of the insulator. Dielectric strength was measured in voltage divided by electrode separation distance, kV/mm. The resulting design had to have a high enough dielectric strength to pass the dielectric withstand voltage. The path of concern was the shortest direct path through the volume insulation from the electrode to ground or another metal at a different potential.

5.4 Testing Requirements

The Electronic Components Industry Association (ECIA) standard for test procedures for electrical connectors, EIA-364, replaced the military written standard MIL-STD-1344 [82]. All the connector specific tests that needed to be carried out followed the EIA-364 standard [83]. MIL-STD-1353 stipulated that any supplemental testing that may be deemed necessary should be done according to the MILD-STD-202, "Test Method Standard Electronic and Electrical Component Parts".

Detail specifications list the testing requirements for each specific type of connector. Since the high-power shipboard connector was the first of its kind, a brand-new set of detail specifications was needed to be set and reviewed in the testing phase of the design process. A full list of testing requirements and specifications would need to be compiled. Below is a starting list of necessary tests for the connector based on the detail specification for the circular connector quick disconnect 38999 series [84] .

EIA-364:
Contact Resistance Test
Withstanding Voltage Test
Insulation Resistance Test
Maintenance Aging Test
Mechanical Shock Test
Vibration Test
Contact Retention Test
Humidity Test
Thermal Shock Test
Impact Test
Magnetic Permeability Test
EMI Shielding Effectiveness Test
Shell-To-Shell and Shell-To-Bulkhead Resistance Test
Low Temperature Test
Durability Test
Current Overload Test
Dielectric Breakdown Voltage
Mating and Unmating Forces Test

IEC 60529:
Ingress Protection Rating

ASTM D2303:
Insulation Arc Resistance and tracking Test

6 Defining Constraints for the High-Power Shipboard Electrical Connector Concept Design

In pervious sections a review of applicable standards and practices relating to the general design of electrical connectors were presented. This chapter is the application of commercial and Navy standards and practices applied to the high-power electrical connector. First, an application of the water and dust protection applied to the connector design and then specific constraints given the selected electrical parameters of the concept design.

6.1 Water and Dust protection

There was a certain amount of uncertainty surrounding the location where the high-power connector would be employed. Location affected environmental conditions which in turn affected the required IP protection as discussed in 5.2. The concept design was focused on applications greater than 1000 V. Therefore table Table 5-6 gave the pertinent IP design guidance. The connector was designed with the iPEBB in mind, a converter as defined in that table, but was designed for adaptability as it could easily be used in other power corridor applications. The minimum IP protection of the connector therefore was the maximum protection from Table 5-6, IP44, in order to ensure versatility of the connector.

Navy ship machinery spaces were generally more cramped than similar displacement commercial vessels. Switchboards and electrical distribution equipment were often located in machinery spaces classified as wet spaces. Figure 6-1 shows an example of a main switchboard on a commercial vessel compared to the location of a switchboard on a USS vessel. It was highly likely the connector would be applied in some fashion in a machinery space.

Naval vessels had AFFF fixed systems in their spaces and water mist protection for main engineering spaces was increasingly common. DNV standards noted that “electronic equipment enclosures located in reach of fixed water-based local application firefighting systems (sprinklers/water mist) in the protected area and those within adjacent areas exposed to direct spray shall have as a minimum the degree of protection IP44” [77]. Equipment adjacent but not exposed to direct spray may have a lower protection if design layout was taken into account. Therefore, IP44 was the standard protection for the connector based on the connector’s location in a USS machinery space.

Figure 6-1:A switchboard in a commercial ship (left) [85] and switchboard on USS Jackson (right) [86]

The Navy had its own ingress protection standards regarding electrical equipment in machinery spaces the connector needed to meet. Dust in the maritime definition involved combustible dust, where solid combustible material particles presented a fire hazard when suspended in air over a range of concentrations [87]. The military standard for electrical equipment enclosures, MIL-DTL-2036, specified dust protection as a special circumstance not normally found in the shipboard naval environment [88]. Therefore, dust protection was not a factor for the Navy in determining the required IP rating. However, the MIL-DTL-2036 standard addressed protection against access to hazardous parts, requiring protection of personnel against physical contact with electrically energized parts, corresponding to IP3X.

The military standard identified the water protection required in a machinery space as dripproof (45 degrees), meaning the connector could be tilted to a maximum of 45º from its normal position without any harmful effect or water intrusion from sprayed water in accordance with MIL-STD-108. In the IP code there was no 45º standard; IPX2 was for 15º and IPX3 was for 60º. The military standard also identified water protection for equipment protected by sprinkler systems, which could be the case in certain applications of the high-power connector. In those cases, the military enclosure had to be splashproof. The equipment had to function while being sprayed by coarse water from any direction. This corresponds fittingly with IPX4, protection against splashing water.

Weighing the military standards, commercial practices, and incorporating versatility into the connector, a conservative approach was taken. IP44 was selected as the minimum ingress protection rating of the connector, thus the design would have features that passed the similar military and commercial splashproof tests. IP44 surpassed the minimum military standards for electrical equipment in a machinery space and met the commercial standards for any type of equipment over 1000 V in any kind of space. The higher protection was welcomed in this high voltage, high power equipment, as it provided better shock prevention and water intrusion. The versatility of IP44 also allowed the connector to be used in almost any compartment not impacted by outside elements. It could be employed in a machinery space near a sprinkler system or in a well air-conditioned dry electronic space.

6.2 Environmental Parameters

The general shipboard environmental conditions based on shipping classification societies specifications were presented in 5.2. The Navy standard MIL-DTL-917, modified a few of those parameters. The ambient conditions of the connector were based on a machinery pace environment, the harshest condition the connector was anticipated to operate as laid out in 6.1. The resulting design and testing ambient condition parameters were a combination of the MIL-DTL-917 and the classification societies specifications. The final relevant ambient condition parameters are presented in Table 6-1.

Table 6-1: High-power shipboard connector ambient design conditions

Parameters	Design Conditions
Operating Air Temperature	0ºC (32ºF) to 55ºC (131ºF)
Non-operating Air Temperature	-40ºC (-40ºF) to 75ºC (167ºF)
Atmospheric pressure	1000 mbar
Max. relative humidity	100 %
Salt content	1 mg/m^3
Oil vapor	withstand
Condensation	Occurs on equipment

6.3 Electrical Contact Requirements

In order to set additional insulation and connector requirements the contact's electrical requirements were first selected. As an illustration of how the contact selection process from chapter 4 could be used to develop an initial concept design for a useful high-power connector the starting requirement was to create a connector that would be rated for 400 kW using 400 A at 1000

V. The connector was also required to have an allowable maximum power loss of 25 W at 400 A or 0.00625% of full power at 400 A, based on the need to keep minimal heating.

6.4 Creepage Distance

Creepage standards and practices were presented in 5.1. In the particular case for the high-power shipboard connector, the 1000 V potential was in an interesting juncture where the MIL-DTL-917 applied and the surveyed off the shelf connector data was valid. Figure 6-2 shows the various creepage standards around 1000 V DC. The minimum creepage distance requirement was 50.8 mm based on the military standard. The MIL-DTL-917 open standard applied since the connector was assumed to not be enclosed, meaning it was exposed to the free transmission of the surrounding air. The military standard noted that more creepage distance may be necessary if operating in conditions “more severe than normal” [73]. The connector on the iPEBB was to be low maintenance and not be routinely connected or disconnected, therefore the connector was designed with more creepage distance than the minimum requirement.

Three standards were considered and used to base a good creepage goal which would be above the military standard: the “High Creepage” connector trend line, the upper outdoor HVDC survey line, and the IEC 60092 switchboard standard. The “High Creepage” trend line as established in 5.1 was made from the higher power connector serving in more intense application conditions. This trend line intersected 1000 V at a creepage distance of 61.7 mm.

The military standard above 1000 V was IEC 60092, which stated the required creepage distance for 300 V PTI material operating under 1100 V was 26 mm. It increases the distance to 63 mm between 1100 and 3300 V. The stepwise function did not offer clarity on the lower end of the voltage step range.

Finally, the HVDC survey showed the high end of the creepage distance on outdoor insulation for 1000 V as 51 mm. This equipment was exposed to the outdoor weather elements; not the same conditions as the shipboard environment.

The creepage distance goal for the high-power connector was set to 60 mm after taking into account all of the above into considerations. This goal satisfied the military standards just above and below 1000 V. It was stricter than the standard accounting for the possibility of a more severe environment using the “High Creepage” connector data as a guide.

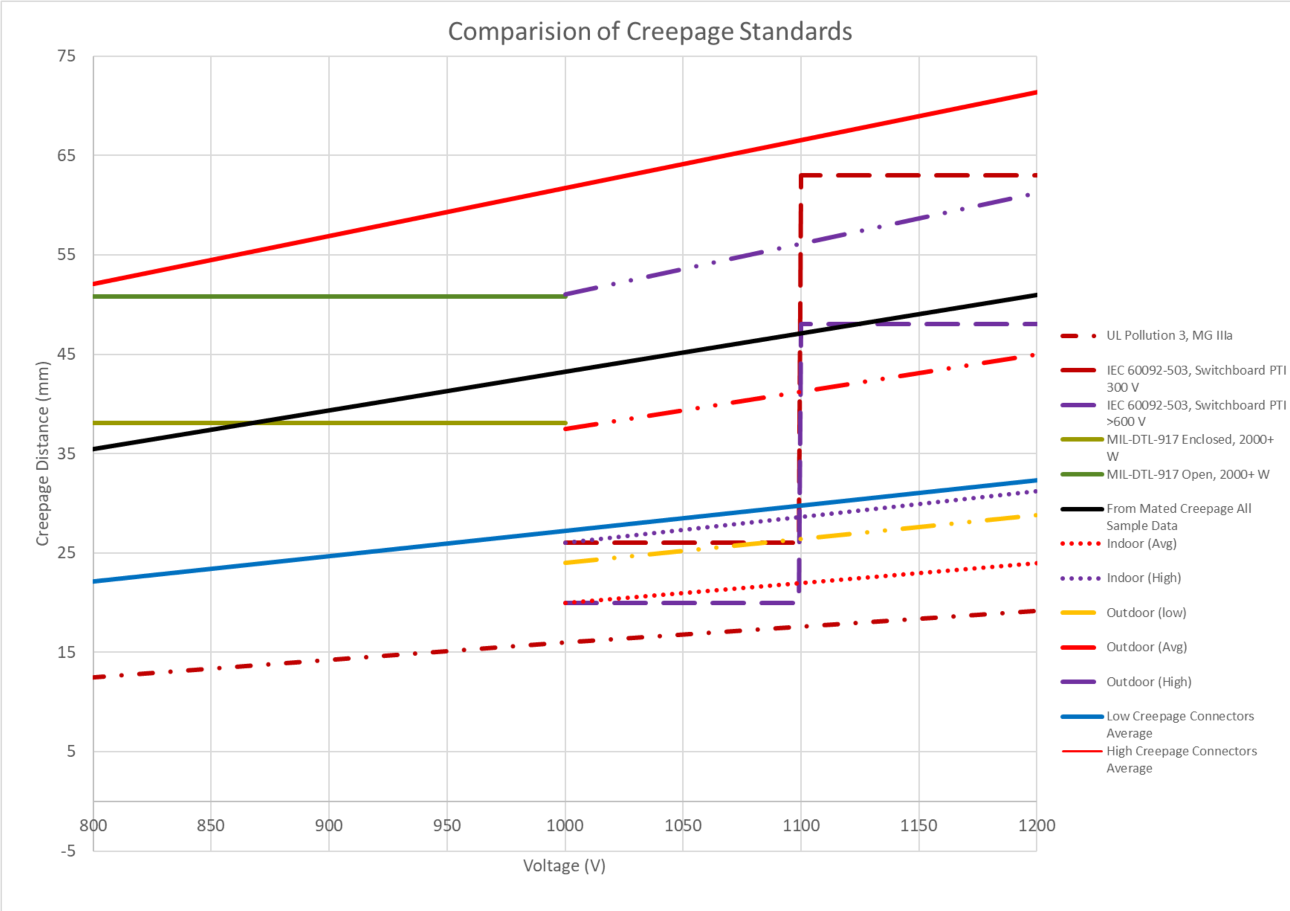


Figure 6-2: Applicable creepage distance standards and trendlines for 1000 V application

The goal creepage distance was compared to other commercial off the shelf connectors directly in Figure 6-3 and Figure 6-4. The goal creepage distance was the more conservative than all existing connectors at 1000 V except for roughneck which was designed for the very dirty work on an oil platform. The goal creepage distance was larger than any connector under 795 kW.

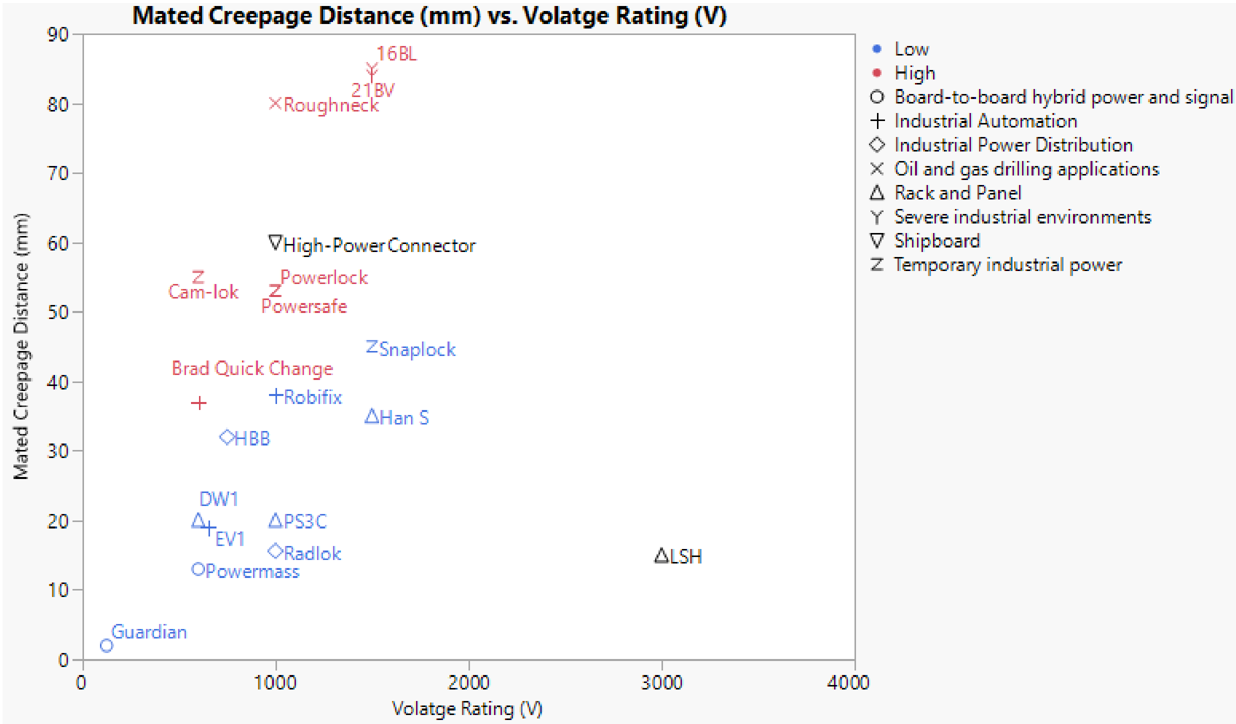


Figure 6-3: Selected goal creepage distance of shipboard connector compared to surveyed connectors rated by voltage

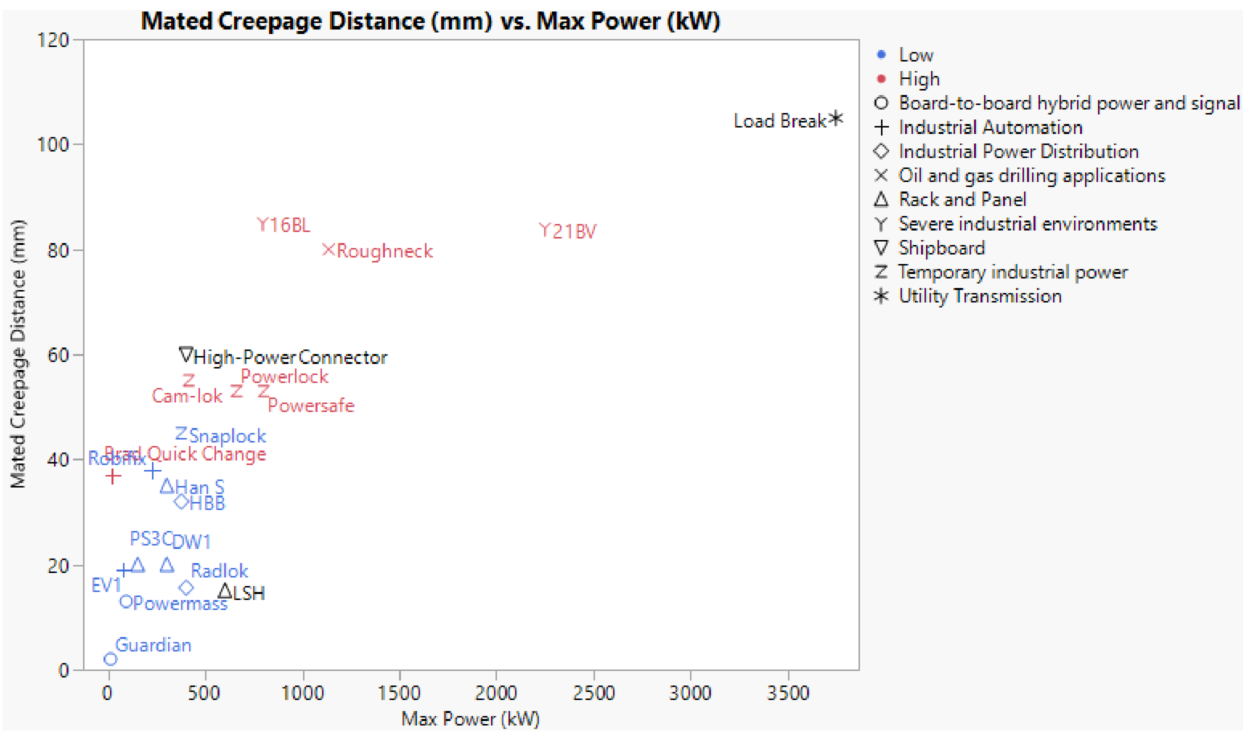


Figure 6-4: Selected goal creepage distance of shipboard connector compared to surveyed connectors rated by power

6.5 Size and mating force

The most important motivating factor for the design of a new a high-power connector was a compact size. Contemporary military circular contacts came in standard insert arrangements. MIL-STD-1651 presented the arrangements that allowed the most current for standard sized military contacts [89]. These arraignments were used in different types of plug connectors which were designed to meet specific conditions. For example, MIL-DTL-22992 connectors were waterproof quick disconnect type plugs and receptacles but were limited to 200 A [90]. SAE AS50151 which replaced the military specification, MIL-DTL-5015, were not inherently limited in current capacity and therefore reaped all the benefits of the different contact arrangements in MIL-STD-1651. According to the MIL-STD-1651, the smallest arrangement that could theoretically support at least 400 A using standard military contacts was insert arrangement 32-63, shell size 32. Therefore, the new high-power connector needed to be no larger than military shell size 32 of a wall mounted receptacle. A drawback to the 32-63 insert arrangement was that it consisted of five separate contacts each capable of carrying only 80 A. By using one single pole contact the size of the connector could be decreased and the complexity of dividing and combining currents, along with the possible added resistance it posed could be avoided.

The size of a wall mounting receptacle shell size 32 is depicted in Figure 6-5. The maximum outer diameter of the high-power connector was to be less than 80.61 mm which included the area necessary to attach to the iPEBB chassis. The outer diameter of the high-power insulation mating interface was set to be less than the inner diameter of shell size 32, 44.96 mm. The maximum outer diameter of a shell size 32 insulation mating interface, as depicted in Figure 6-6 was 60.1 mm.

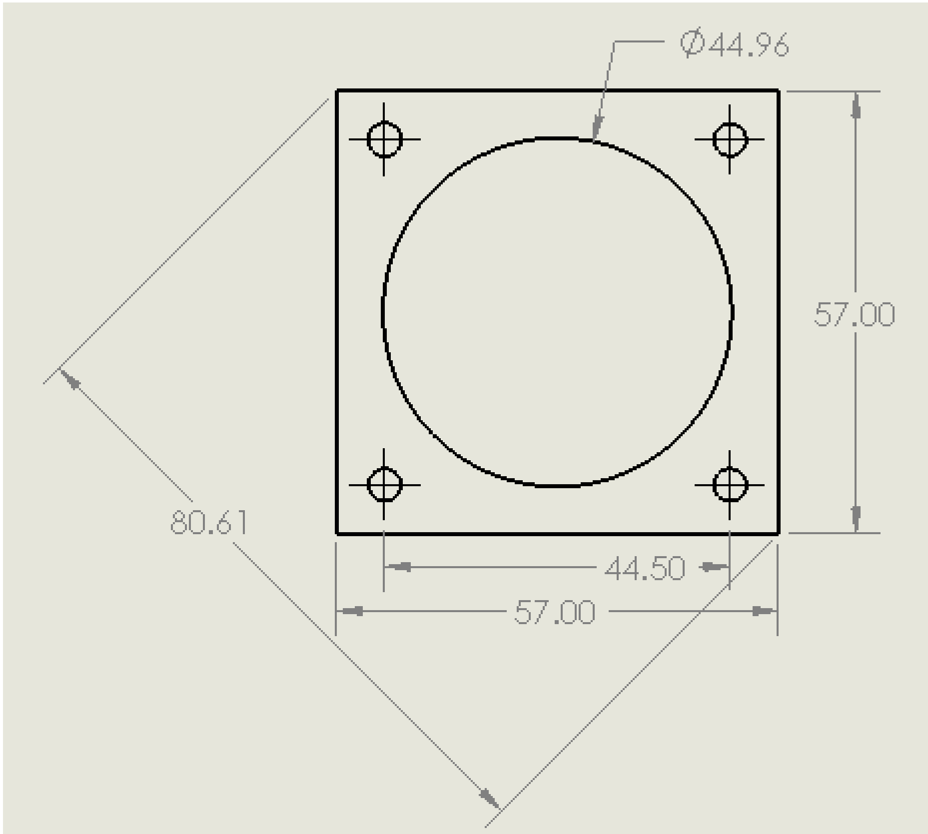


Figure 6-5: Shell size 32 wall mounted receptacle dimensions, all dimensions in mm

Figure 6-6: The outer diameter mating interface of an Amphenol reverse bayonet coupling connector [91]

Another important parameter that needed to be selected based on standards was insertion and mating forces. The largest standard single pole contact used in arrangements previously specified was size 0, which used a 9.068 mm (0.357 in) solid diameter pin. The engagement force for that contact was 88.96 N (20 lbf) [92]. Therefore, the maximum insertion force for the single pole contact was set to 89 N (20 lbf). The total mating force of the connector was based on increasing the mating resistance by 25% of the contact maximum insertion force, 111 N (25 lbf). This was right around the recommended upper force limit of 24 lbf for horizontal pushing as prescribed by Canadian Centre for Occupational Health and Safety (CCOHS) for applications where only the arms were involved in the process [93]. For application on the iPEBB, two single pole DC connectors would be needed, totaling a maximum insertion force of 222 N (50 lbf). The average Sailor would be able to exert this force using their whole body [93] or helped in their effort through a mechanical advantage mating mechanism. Table 6-2 presents a summary of size and mating force parameters.

Table 6-2: Size and mating force parameters

Parameter	Design Condition
Maximum outer diameter (including chassis mating interface)	80.61 mm
Maximum outer diameter of the insulation mating interface	44.96 mm
Maximum contact mating force	89 N
Maximum total mating force	111 N

6.6 Electric Insulation

Previously in section 5.3 specific insulation parameters were identified based on military standards for a shipboard specific connector. The minimum requirements are reproduced in Table 6-3 and Table 6-4.

Table 6-3: Insulation design parameters for the high-power shipboard connector

Parameter	Design Condition
Insulation Resistance	> 10 megohms at 77ºF
Dielectric Withstand Voltage	Twice the rated voltage of the circuit plus 1000 V
Arc Resistance (<2000 V)	130 sec. minimum
Tracking resistance (<2000V)	70 minutes minimum

Table 6-4: Flammability requirements for the high-power shipboard connector

Flammability Limit
Ignition: 95 sec. minimum
Burning: 120 sec max.
Weight loss: 15% max. Ratio
Burning time: 10 sec. max.
Extent of burning: 25 mm max.

7 Concept Design, 1 kV, 400 Amp

7.1 Design Priorities

Design priorities were selected before the design process began in earnest. The six priorities in descending order of importance were: Compact Design, Minimal Power Loss, Water and Dust Protection, Low Mating Force, Misalignment Tolerance, and Mating Confirmation/ Secure Closer. Making a smaller more compact design was the top priority as it was one of the primary reasons for investigation into the high-power shipboard connector. Minimalizing the power loss was beneficial for efficiency of the connector in transmitting power, but it also kept resulting heat radiation low as well. Minimizing the heat produced meant it contributed less to the cooling load the cabinet or space had handle which was especially important when many iPEBBs and connectors were densely concentrated.

Water and dust protection was vital in order to keep the connector free from moisture and particles which could degrade the connection or cause it to catastrophically fail. The connector was designed with minimal maintenance and cleaning in mind. Maintenance would only be necessary when it was mated and unmated naturally over the lifetime of the iPEBB. The mating force was selected to be low as to minimize the force contribution that would be necessary to mate the iPEBB. The mating of the electrical connector was not to be the greatest factor in terms of force when a Sailor put an iPEBB in place.

The electrical connection process of inserting an iPEBB in place would be done through a blind mate, meaning the contacts would not be visible to the Sailor connecting them. They would be in the back of the iPEBB as it was slid into place. There needed to be room for some amount of misalignment to help guide the connector and contact if the connector was approached from a slight angle or offset. Finally, ensuring the contact was mated without viewing it would be beneficial. Alignment and mating confirmation were lower priorities because other mechanisms on the iPEBB, such as physical mating and locking mechanisms could supplement the electrical connector design. Guide rails and the use of a locking mechanism in the cabinet for example could ensure accurate mating of the electrical contact and could give audio and visual mating cues.

7.2 Electrical Contact Selection

An off the shelf electrical contact was selected as the first step of the concept design. The process and important criteria of an effective electrical contact from chapter 4 plus the constraints from chapter 6 were factored into the selection. A full contact and a louver only contact were picked initially. Three of the top performing Multilam louvers at 400 A were selected for comparison along with the other louver contacts. FOM4 was plotted against contact diameter at 400 A, Figure 7-1, to get an idea of where the contacts fell in terms of an overall design. Then FOM1 and FOM2 were plotted against diameter, Figure 7-2 and Figure 7-3 , to specifically hone in on current density and power loss respectively.

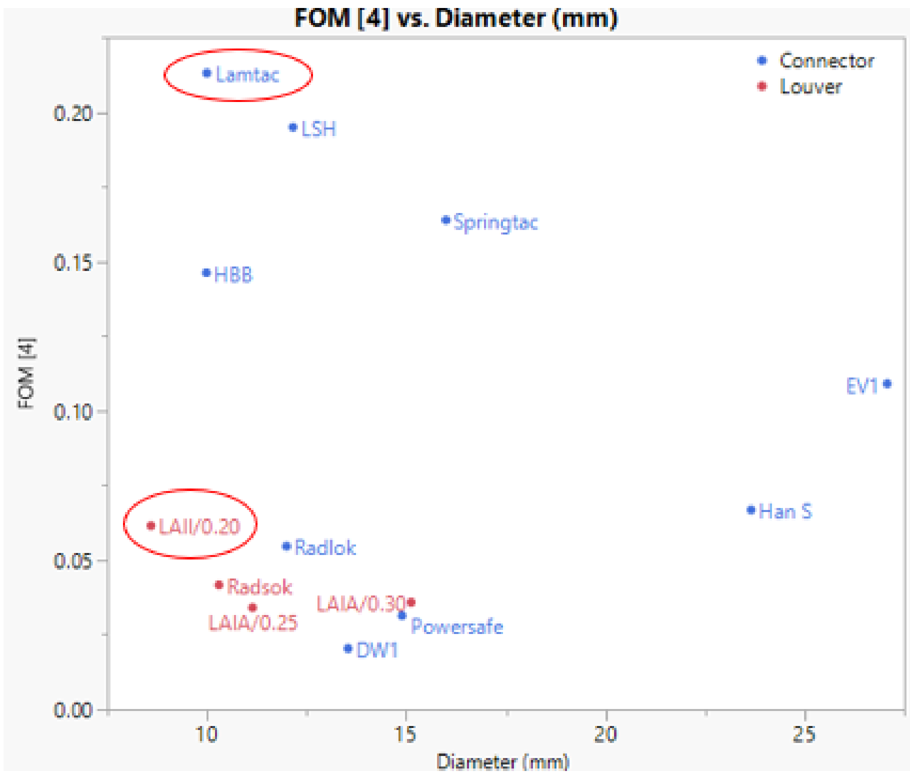


Figure 7-1: FOM4 and diameters of 400 A contacts

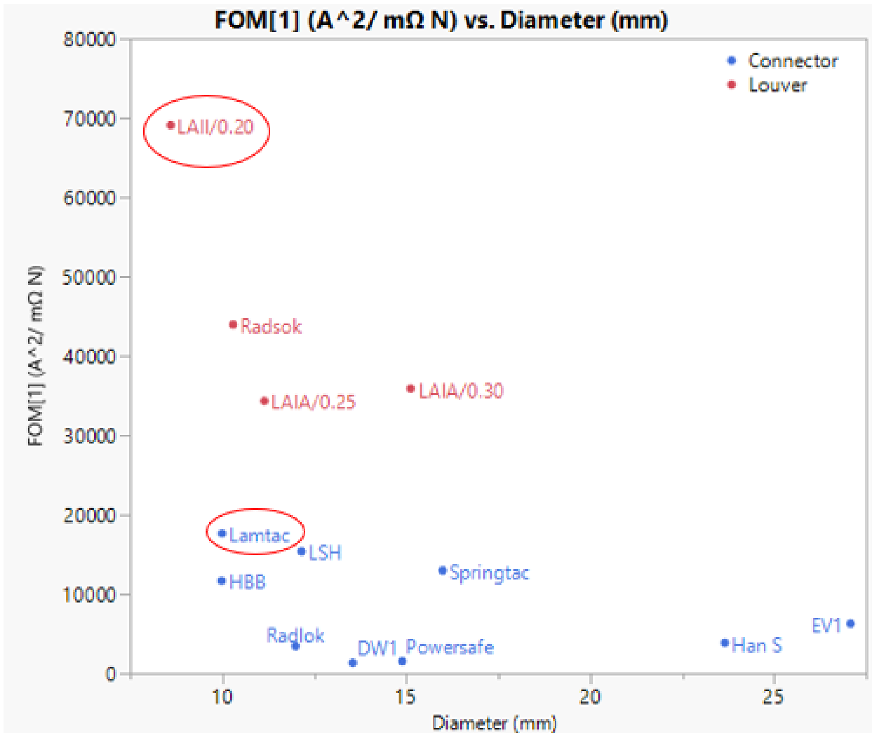


Figure 7-2: FOM1 and diameters of 400 A contacts

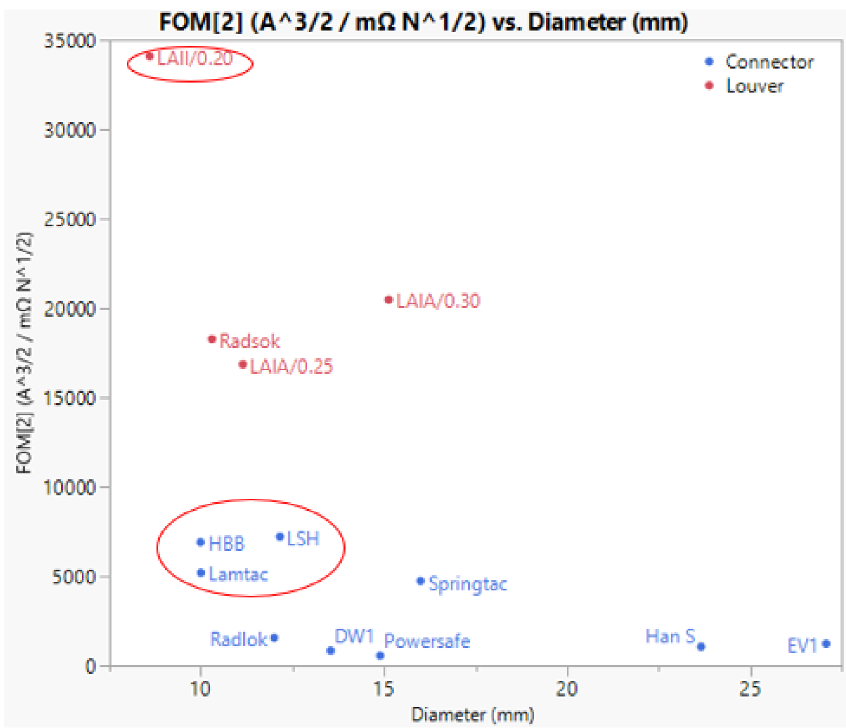


Figure 7-3: FOM2 and diameters of 400 A contacts

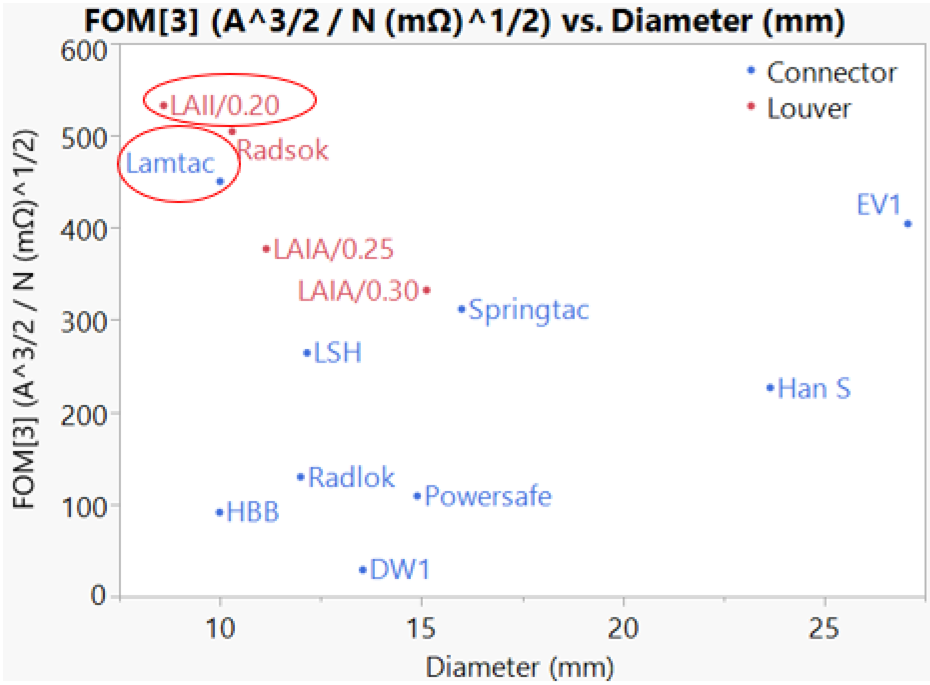


Figure 7-4: FOM3 and diameters of 400 A contacts

Based on the FOM graphs, LAII/0.20 stood out as the best louver contact. It scored the highest in each FOM category and was the smallest in terms of contact diameter. Out of the full contacts that were compared, Lamtac was tied for the smallest in diameter and had the highest FOM score in FOM1, FOM3, and FOM4. It scored lower than HBB and LSH on FOM2, which emphasized power loss. Since compact design was the number one priority LSH was ruled out in favor of Lamtac due to its size. HBB was ruled out in favor of Lamtac because of its significantly lower score in FOM4, a result of HBB's high mating force. Table 7-1 in conjunction with Figure 7-5 show the precise measurements of the contacts at 400 A for verification that the chosen contacts met the design constraints.

Table 7-1: Contact properties at 400 A

Contact	Round Contact "Diameter" (mm)	Current Capacity of contact (A)	Resistance of contact (μΩ)	Sliding force of contact (N)	Power dissipation (W)
Springtac	16.00	535.00	130.00	45.00	20.80
Lamtac	10.00	410.00	100.00	30.00	16.00
LSH	12.16	400.00	50.00	88.00	8.00
HBB	9.99	402.78	62.07	140.97	9.93
DW1	13.55	403.85	247.62	161.54	39.62
Powersafe	14.90	413.79	604.17	53.79	96.67
Han S	23.66	400.00	150.00	30.00	24.00
EV1	27.08	406.15	147.73	15.56	23.64
Radlok	12.00	400.00	235.71	81.67	37.71
Radsok	10.30	405.00	30.00	70.00	4.80
LAII/0.20	8.60	414.00	19.44	100.80	3.11
LAIA/0.25	11.15	406.00	25.00	98.00	4.00
LAIA/0.30	15.13	665.00	15.79	216.13	2.53

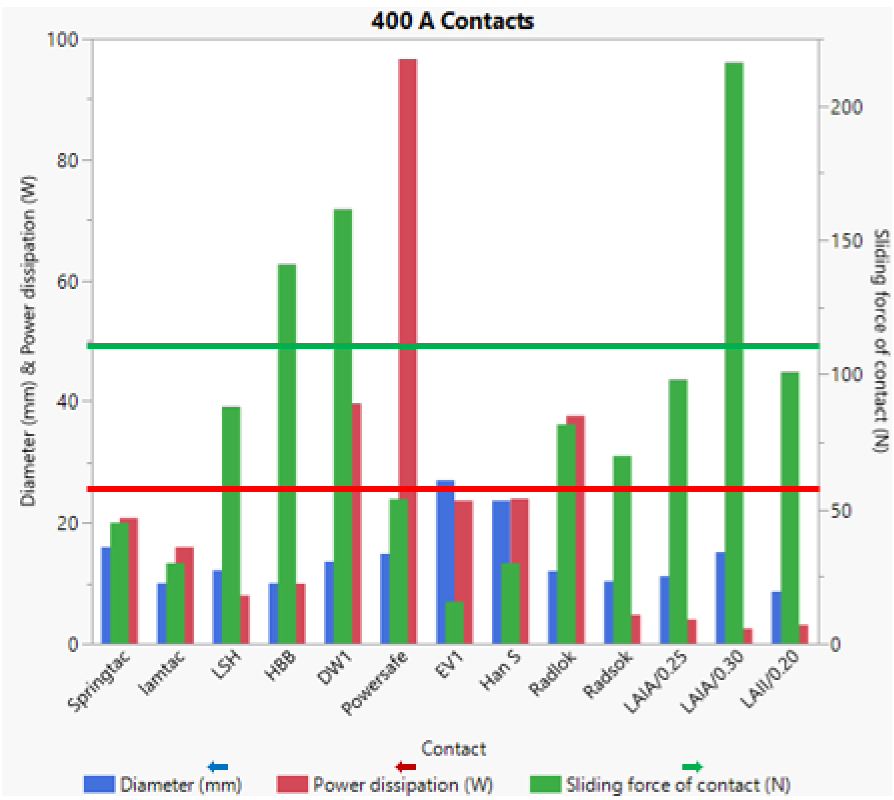


Figure 7-5: Graphical view of 400 A contacts. Red and green horizontal lines show the upper limits for power dissipation and sliding force.

The HBB, DW1, and LAIA/0.30 contacts exceeded the maximum mating force. Radlok and Powersafe were eliminated based on maximum power loss criteria. Based on these eliminations and the FOMs as a guide, Lamtac and LAII/0.20 were selected as the best contacts at 400 A.

In order to proceed with the concept design, it was decided that using an existing contact with a pin and socket already developed around the louvers would be best to illustrate incorporating the other design principles and constraints into a concept design. The practicality of knowing the dimensions of the pin and socket would increase the likelihood that the concept design be adopted in future work of the high-power connector. The Lamtac contact was offered as a simple pin and socket with no insulation. The concept design involved creating an insulation housing that met design parameters.

7.3 Inspiration for the Design

The connector was designed around the existing Lamtac contact. The largest challenge was how to extend the creepage distance in the mated condition. Existing designs employed a common practice of surrounding the contact and pin in three concentric cylinders located on the male and female side of the connector. The concept is displayed in Figure 7-6 and Figure 7-7, where the pin was surrounded by one cylindrical barrier. The socket was surrounded by two, one right next to the socket and the other was the outer case and encircled the connecting pin cylindrical ring. By creating several concentric cylinders, the creeping distance was essentially doubled with the addition of the first and extended further with each new ring added. This prevented the necessity of having to develop a very long overlapping mating interface in order to achieve the required creepage distance. It allowed creepage distance to be easily extended even with a very short pin and shallow socket.

Figure 7-6: Concentric cylinder concept on the RobiFix by Stäubli [94]

Figure 7-7: Concentric cylinder concept on a GT series reverse bayonet coupling connector [91]

The second major challenge was how to make the connector water and dust protected. As discussed in 2.4 four protection mechanisms were found through the connector survey. Each mechanism could be employed with the above creepage extension mechanism of concentric cylinders. Depending on the insulation materials selected the three fingered concentric circle could form a water tight seal or a gasket could be placed inside to form a water and dust barrier.

The permanent connection mechanism between the iPEBB printed circuit board (PCB) and the high-power electrical contact was not defined. As reviewed in 2.1, there were multiple ways to connect the contact to the PCB including crimping (compression), soldering (fusion), and bolting (mechanical). Upon reviewing existing connectors, it was decided two types of permanent ending mechanisms would be included in the concept design. Examples of existing connectors showing a threaded end and a lugged ending to the contact are in Figure 7-8.

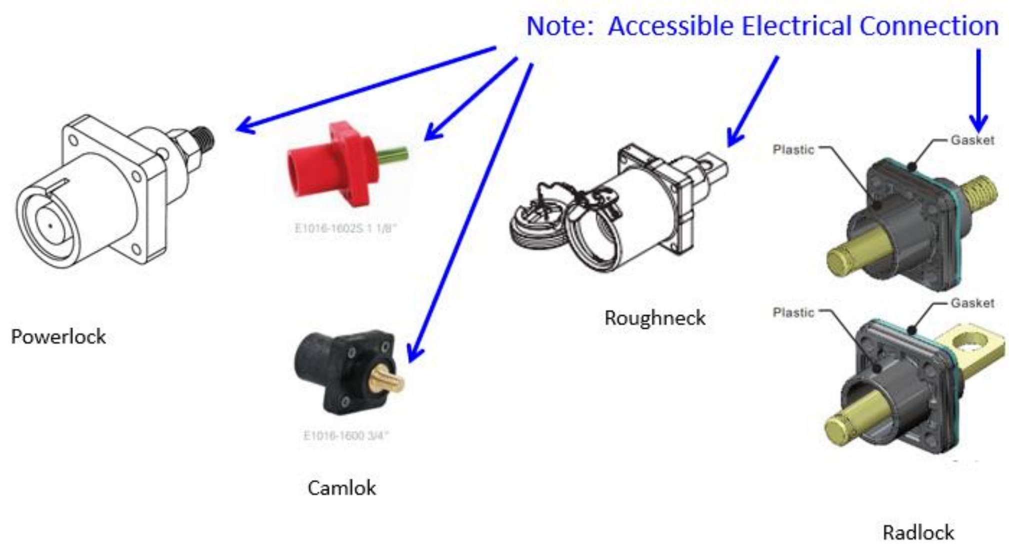


Figure 7-8: Existing connectors with threaded and lugged end points

The exact method of mounting the thread or lugged contact to the PCB was undecided, therefore the multiple options give future designers the flexibility to choose the mounting mechanism. An example of potential PCB mounting hardware was found that could handle 320 A and could be the basis for a design for mounting the threaded contact, Figure 7-9. Based on the state of the practice it was assumed that leaving 20 mm of thread would be enough for mating to the PCB in the iPEBB.

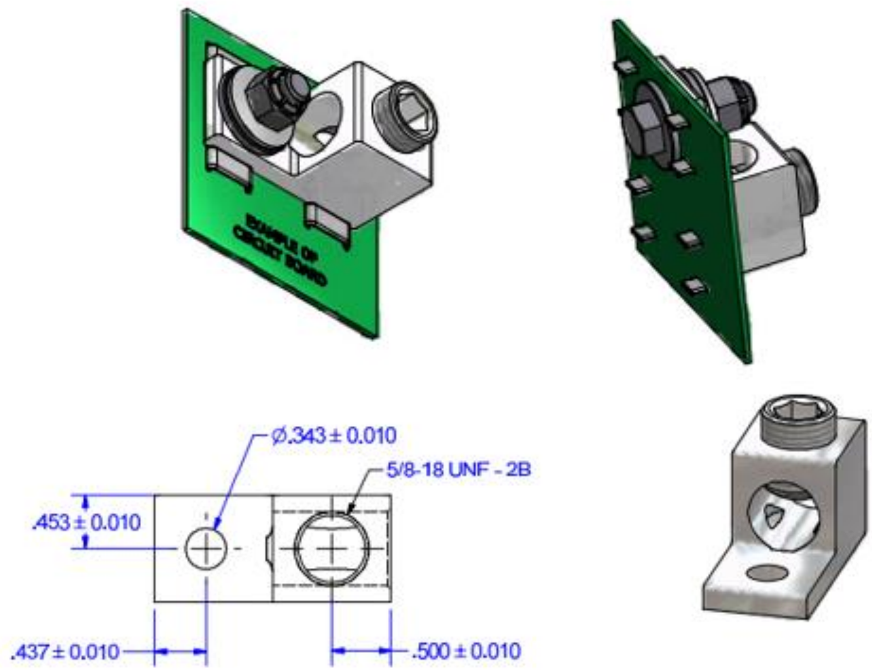


Figure 7-9: A high current PCB mount developed by International Hydraulics, Inc [95]

7.4 Pin Connector Concept Design

The off the shelf ODU Lamtac 10 mm pin dimensions as described in the ODU catalog are pictured in Figure 7-10 [15]. They had to be modified in order to accommodate 20 mm of available thread and maintain at least the minimum creepage distance of 60 mm. The resulting custom ODU pin is shown in Figure 7-11. It had the same dimensions as the off the shelf pin except for an extended unthreaded body between the collar and the start of the threads. The custom threaded socket, lugged pin, and lugged socket configurations are presented in Appendix D.

7-14.

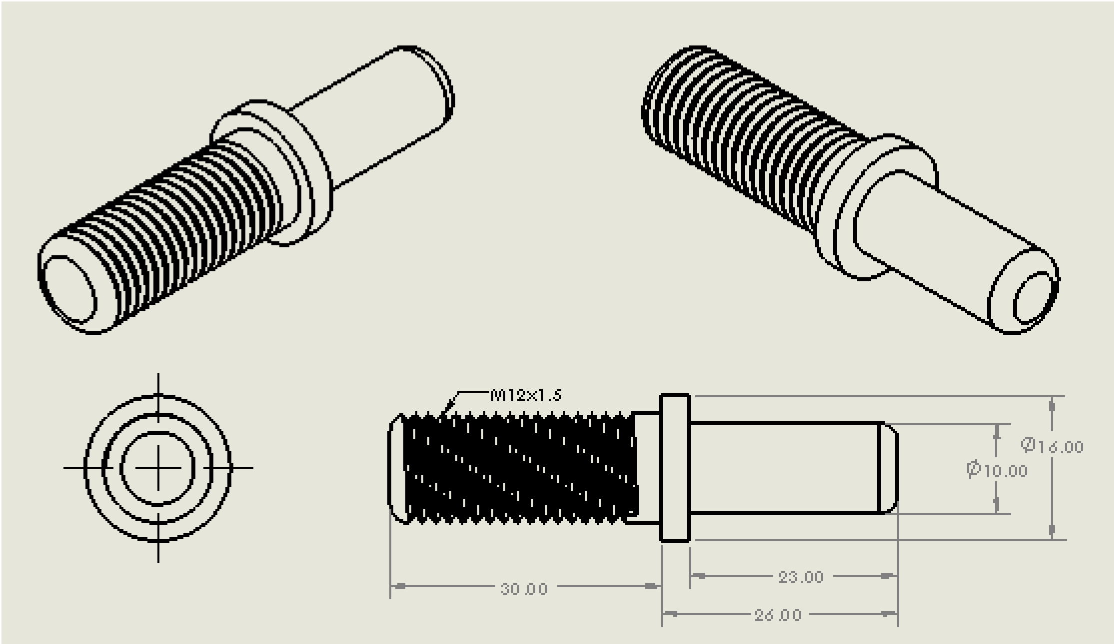


Figure 7-10: Off the shelf ODU 10 mm pin, dimensions in mm

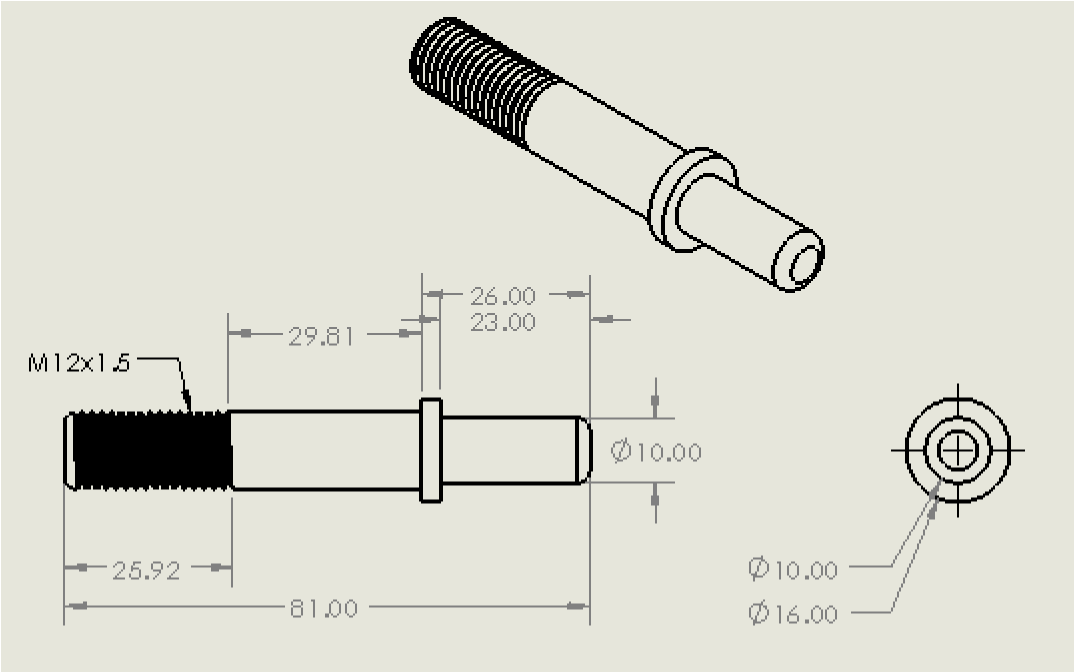


Figure 7-11: Customized 10 mm Pin, dimensions in mm

The concept design of the pin side insulator is presented in Figure 7-12, Figure 7-13, and Figure 7-14.

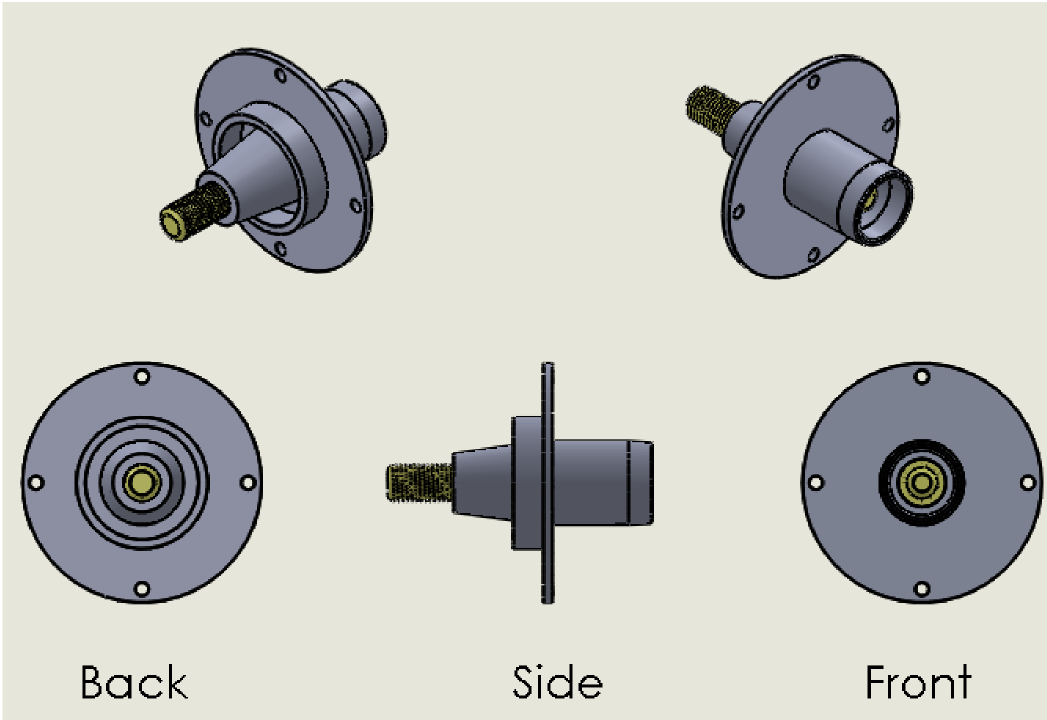


Figure 7-12: 10 mm pin in concept design insulator

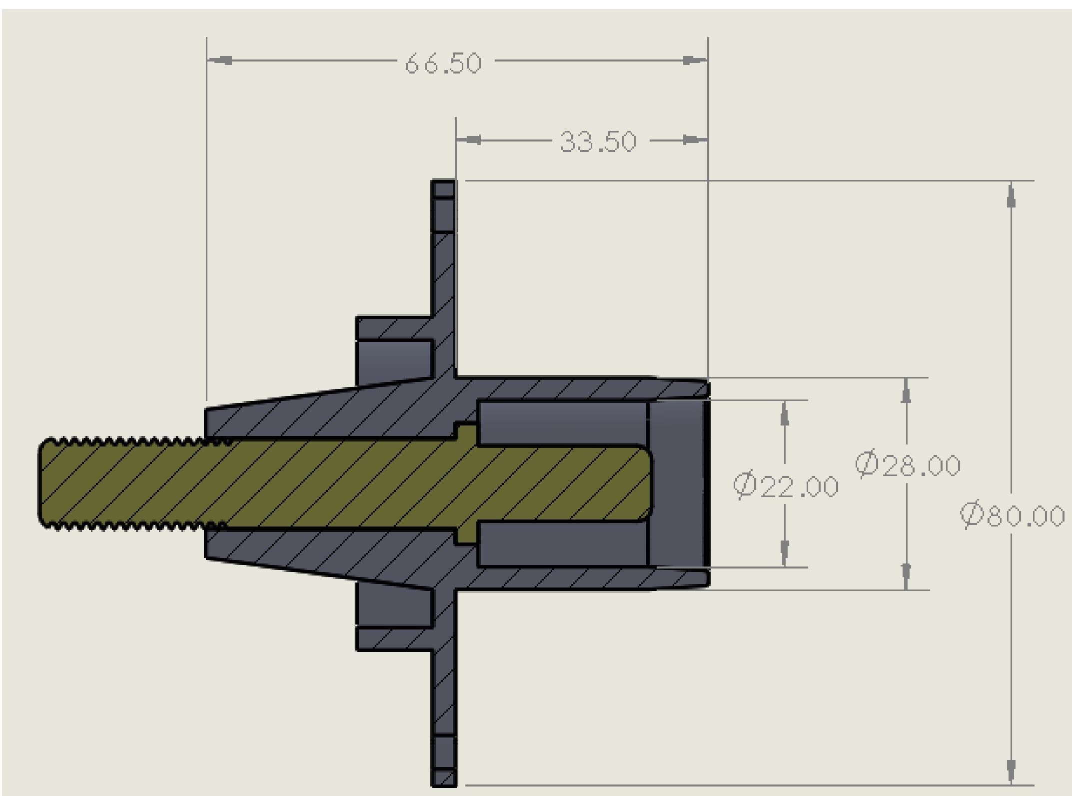


Figure 7-13: Pin insulator, dimensions in mm

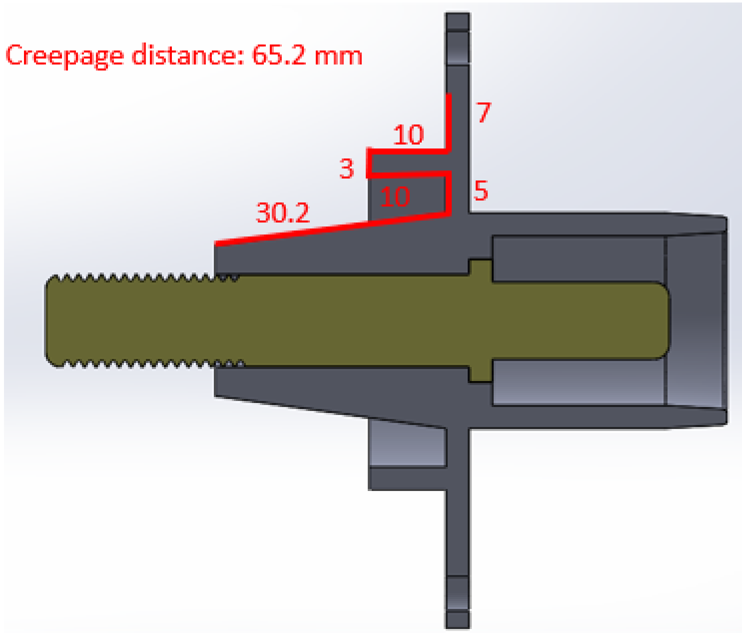


Figure 7-14: Creepage path on the pin insulator in mm

7.5 Socket Connector Concept Design

Like the pin, the off the shelf socket had to be customized for the connector. Figure 7-15, Figure 7-16, and Figure 7-17 show the socket side insulator concept design. The socket was designed to be mounted in the insulator in a tight permanent-press fit.

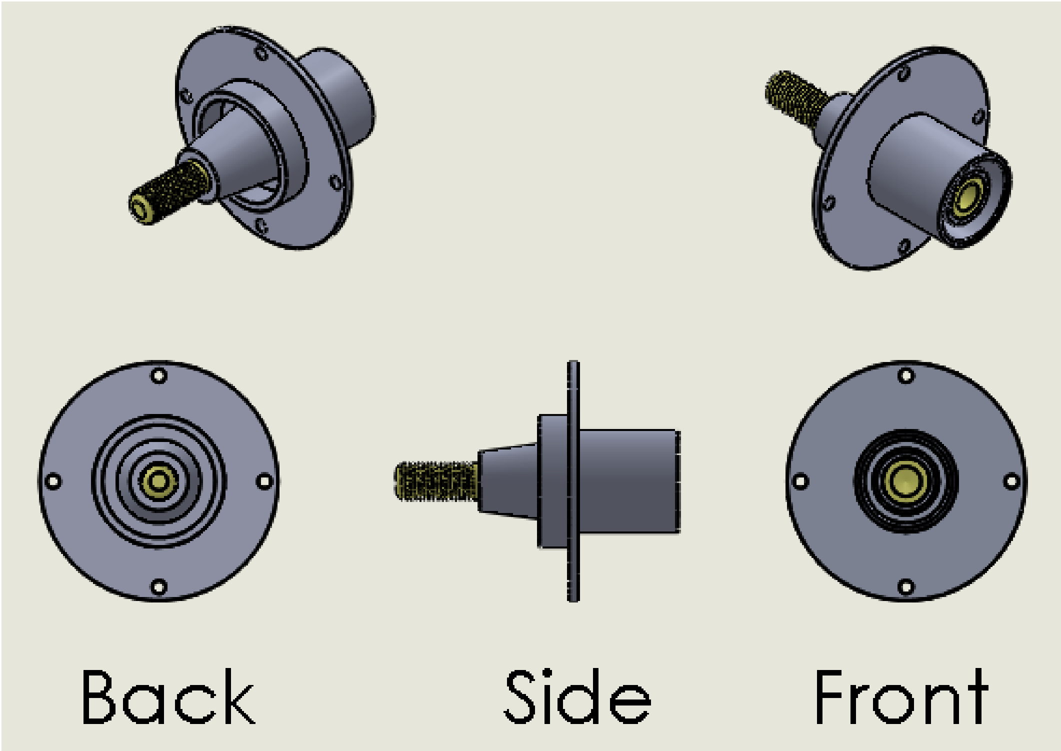


Figure 7-15: 10 mm socket in concept design insulator

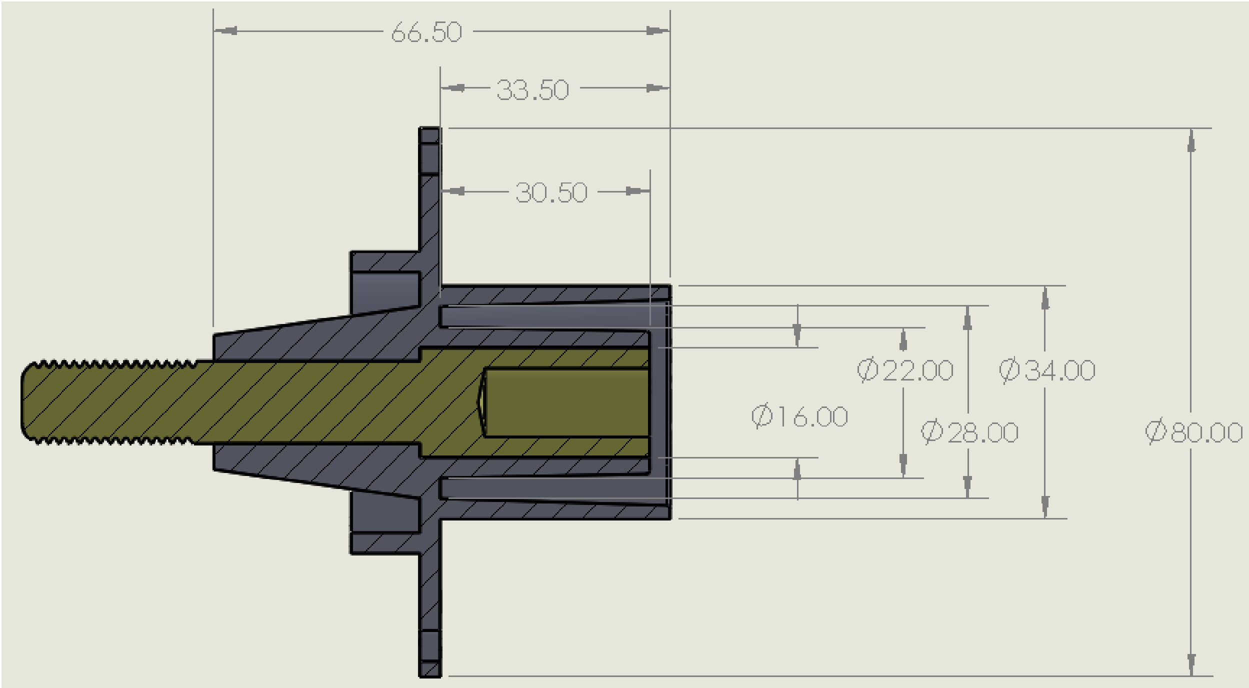


Figure 7-16: Socket insulator, dimensions in mm

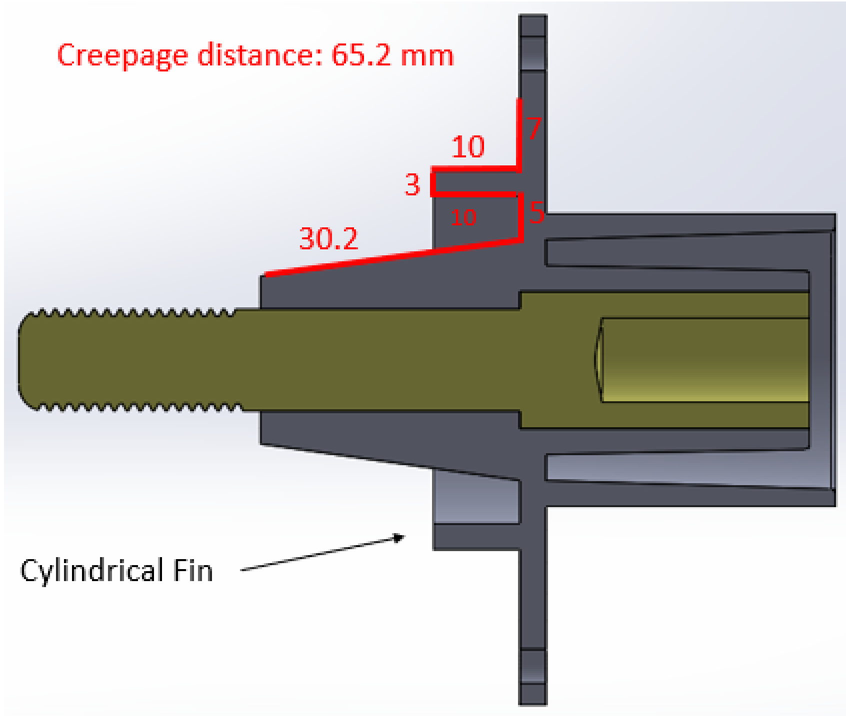


Figure 7-17: Creepage path on the pin insulator in mm

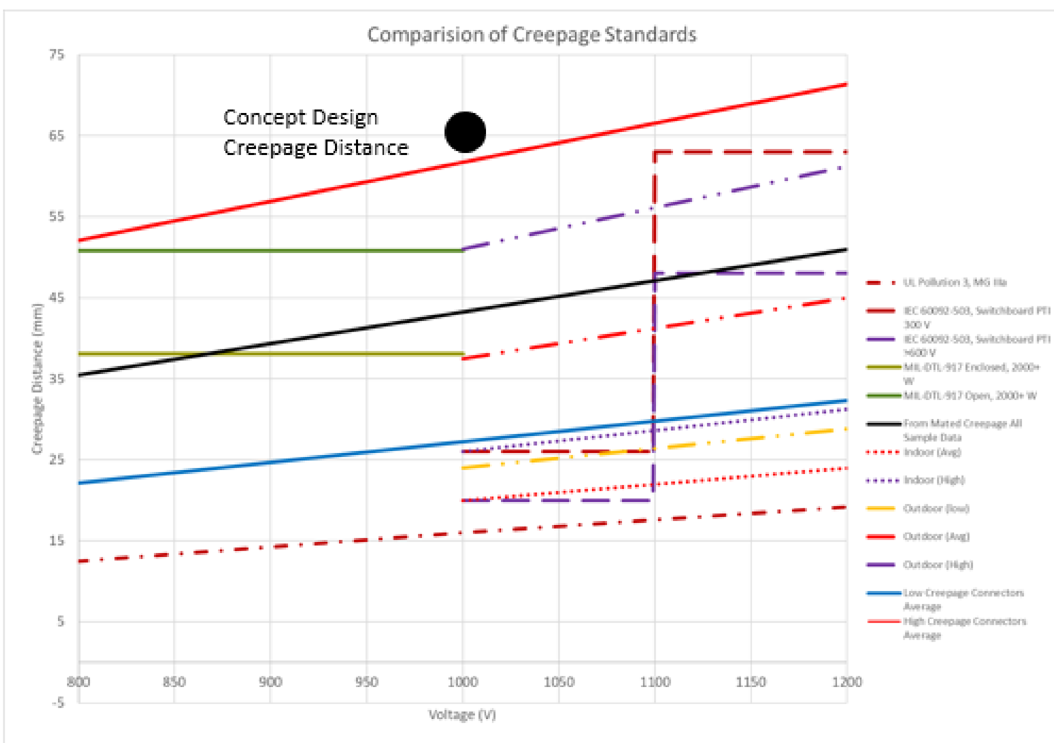


Figure 7-18: Concept design creepage distance compared to standards and trendlines around 1000 V

The creepage distance on the iPEBB interface side of the socket and pin insulator were made using the same geometry resulting in a distance of 65.2 mm. This exceeded the military standards at both 1000 V and 1100 V, and the goal set at 60 mm. Through the use of a cylindrical fin on the connector's interface side the creepage distance was extended by 23 mm. This fin created flexibility in the design as it could be widened or heightened to increase creepage distance as necessary. It could also be shrunk or removed to save space and material cost if during testing the creepage distance proved excessive. The tapered collar from the main flange to the start of the threads could also be modified in future iterations. If the pin or socket needed to be extended or shrunk to accommodate the PCB interface, the tapered collar could accommodate the change. The tapered collar and fin gave flexibility to the design for future modifications involving creepage distance on the back side of the connector.

7.4.3 Connector Mating

The three insulation cylinders, one on the pin and two on the socket, mated tightly together to form an elongated creepage path that satisfied the military requirements. No extra features to extend the creepage path were needed. The creepage path is shown in the mated condition in Figure 7-19. An isometric 3D view of just the mated connector is depicted in Figure 7-20.

The concentric cylindrical approach offered dust and water protection by virtue of the tight fit and 70.5 mm distance that would have to be penetrated in order to reach the outside of the electrical contact when connected. Additional water and dust protection could be incorporated by adding a gasket at the point where the two shells had the most contact and formed a "ring" of friction as they were mated, Figure 7-21. This point was the point of tightest fit in the connectors. A gasket would be an inexpensive way to improve the IP protection of this concept design.

In order to ease the mating process, keep mating forces low, and allow for some misalignment correction, the edges of each conical cylinder were tapered and filleted to correct the sliding path of connector through the mating process. The friction between conical cylinders faces was an issue identified in an initial design detailed in appendix E. In the prior design there were three sliding surfaces with a very tight fit which resulted in friction forces easily tripled compared to the final concept design. In this design, the socket was permanently press-fitted in the insulator, thus there were only two friction faces, besides the electrical socket, that contributed to the mating force.

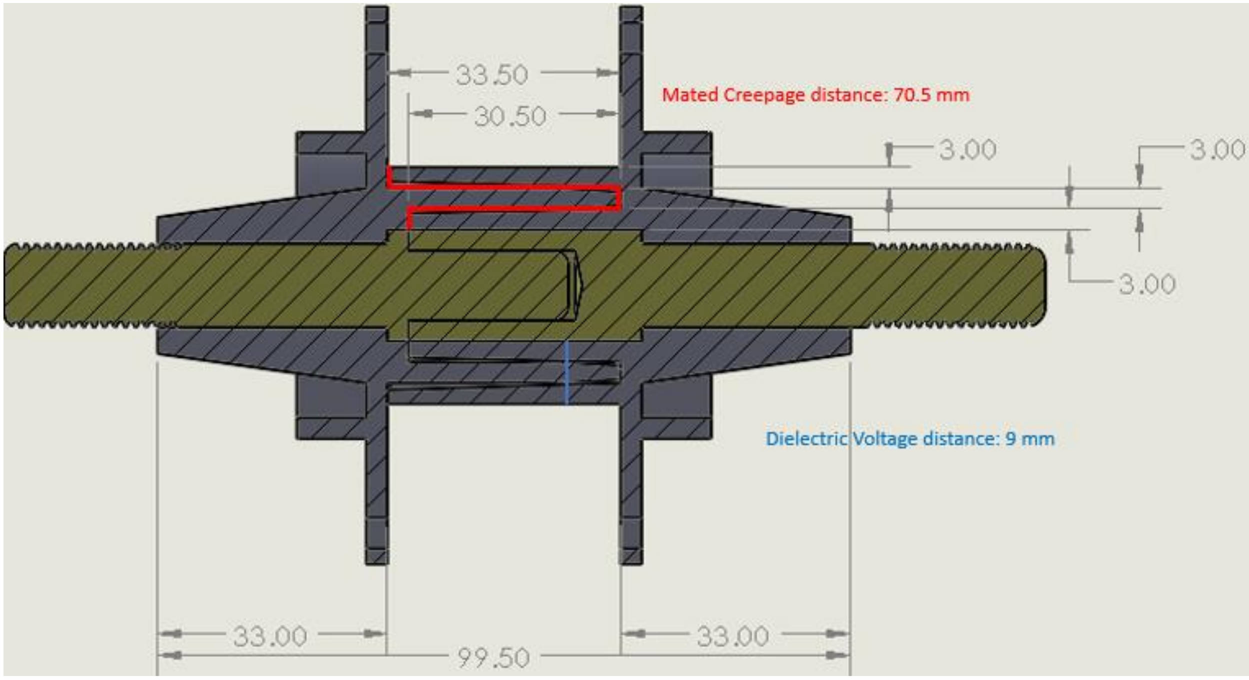


Figure 7-19: Mated concept design configuration

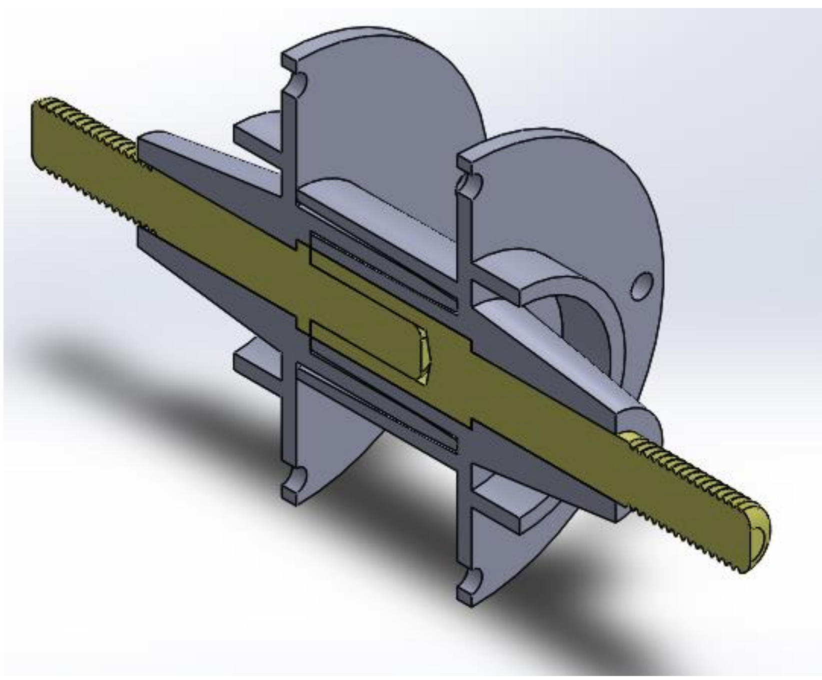


Figure 7-20: Isometric section view of the mated concept design

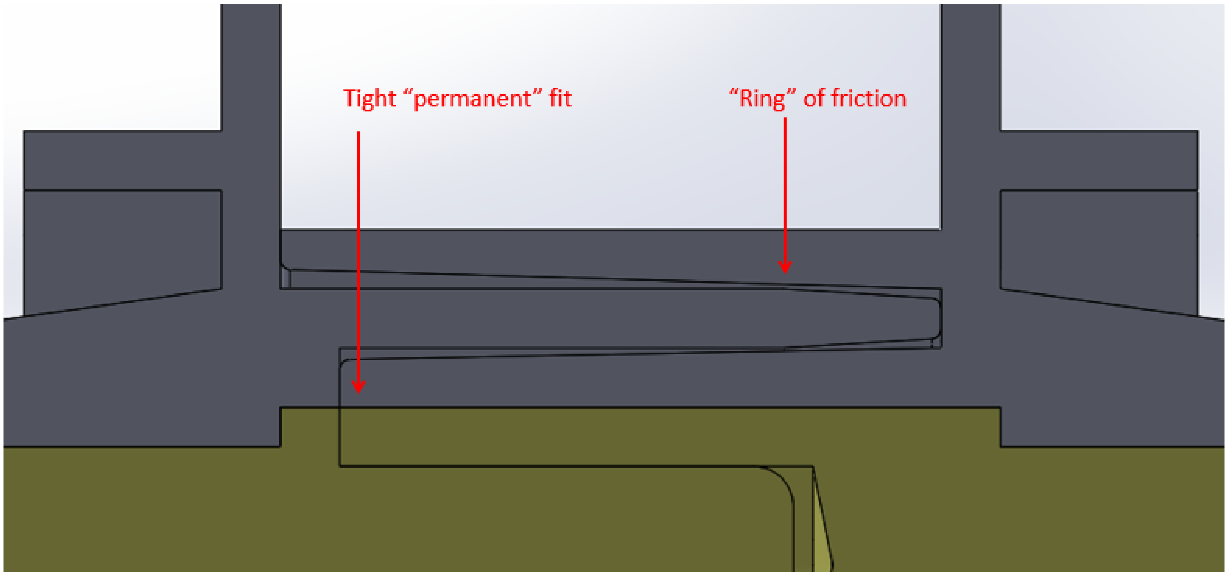


Figure 7-21: Socket was permanently mounted in insulator. Ring of friction created by tight fit between the mating cylinders

The connector mated in stages visually demonstrated in Figure 7-22, meaning the very outside cylinder of the socket connector first made contact and guided the pin cylinder, step 1. This aligned the connector for the second step of the mating sequence when the center prong and socket made contact and straightened it out for the pin and socket contact mating, step 3.

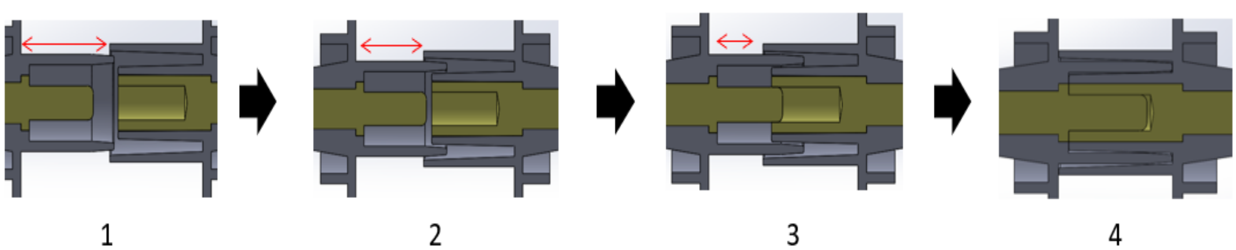


Figure 7-22: The concept connector design mating sequence

The resulting shortest distance through the insulation to a potential grounding point is shown in blue in Figure 7-19. This distance determined the minimum dielectric strength that would be necessary when selecting an insulating material. That minimum thickness and the test voltage for dielectric strength of 3000 V, along with a factor of safety of 10 resulted in a minimum dielectric strength of 3.3 kV/mm. This was a reasonable dielectric strength to expect from insulating polymers [96].

7.4.4 Connector in Chassis

The connector was designed to be mounted on the outside of the iPEBB chassis or other power component. Figure 7-23 depicts an example of how the connector would be mounted to a red chassis. Bolts would hold the connector in place by passing through the blue washer, gray connector flange, and red chassis. The width of the blue washer was 9 mm which would press and seal the connector flange to the chassis. The number of bolt holes and sizes could be modified as necessary.

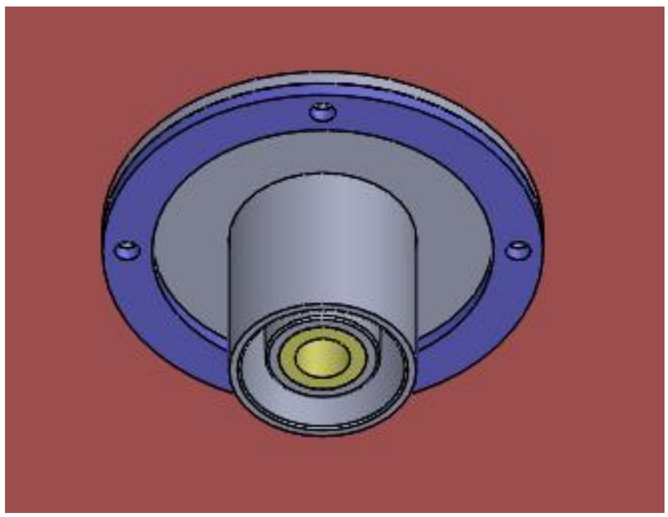


Figure 7-23: Concept Connector mounted on a red chassis with blue retaining washer

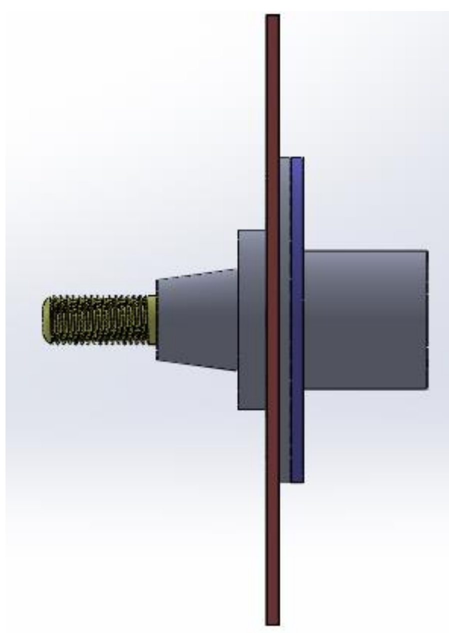


Figure 7-24: Side view of the connector mounted on a chassis

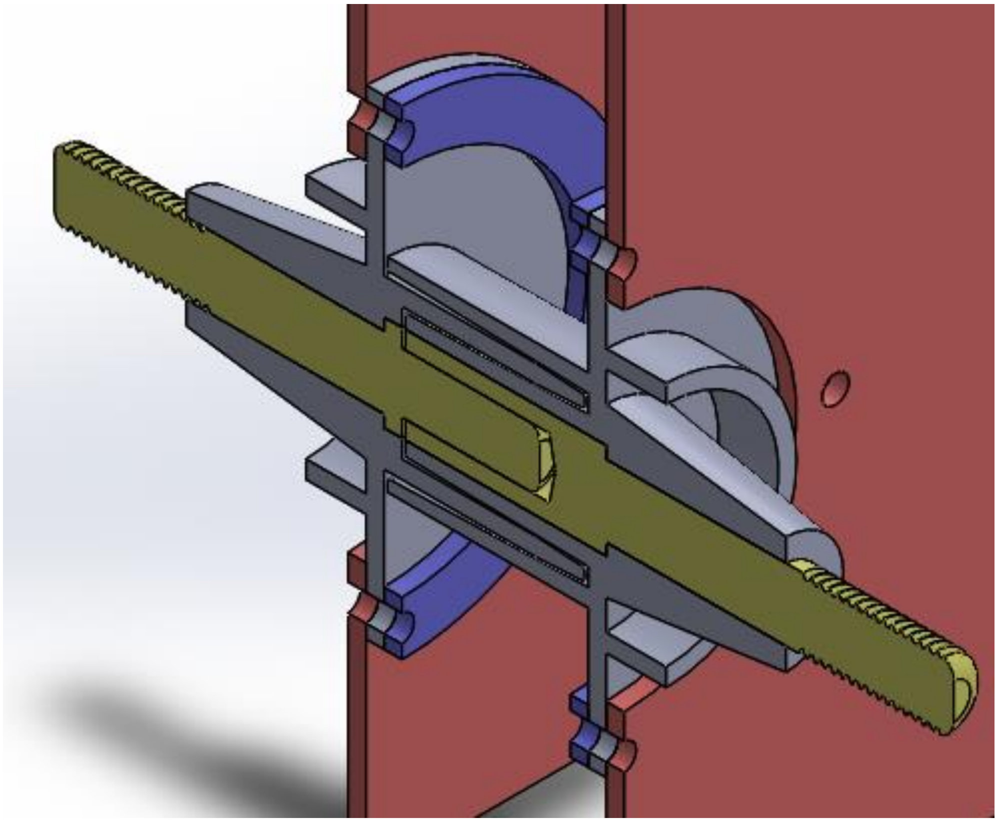


Figure 7-25:Isometric section view of a mated concept connector mounted on chassis

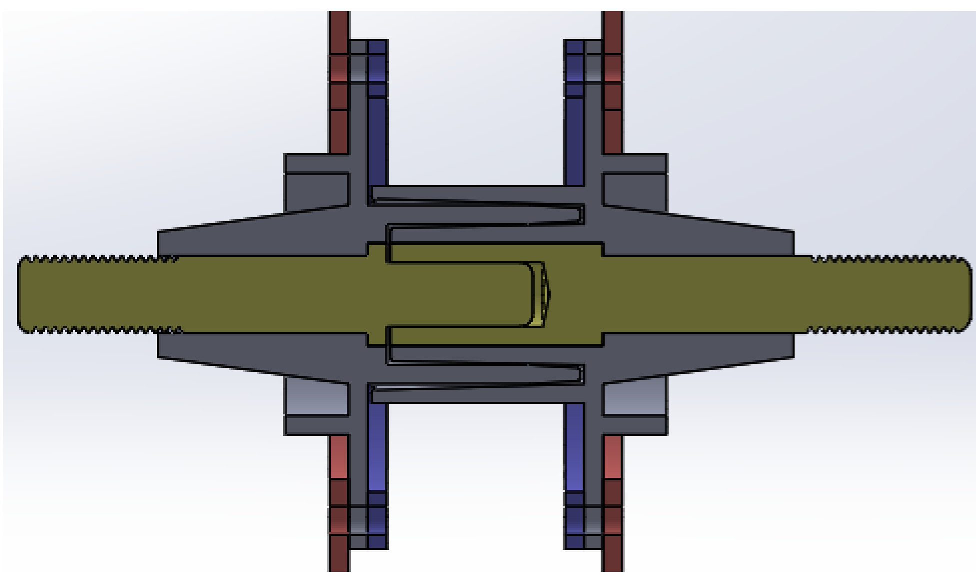


Figure 7-26: Section view of the mated connector mounted on chassis

7.5 Physical Modeling of the Concept Design

The concept design was 3D printed using polylactic acid (PLA) and a Dremel 3D45 printer. The resulting structures provided lessons on how well the connector physically fit together. An off the shelf 10 mm Lamtac pin and socket were used inside the printed connector. The manufactured concept design is shown in Figure 7-27 and Figure 7-28.

Figure 7-27: 3D printed pin concept design

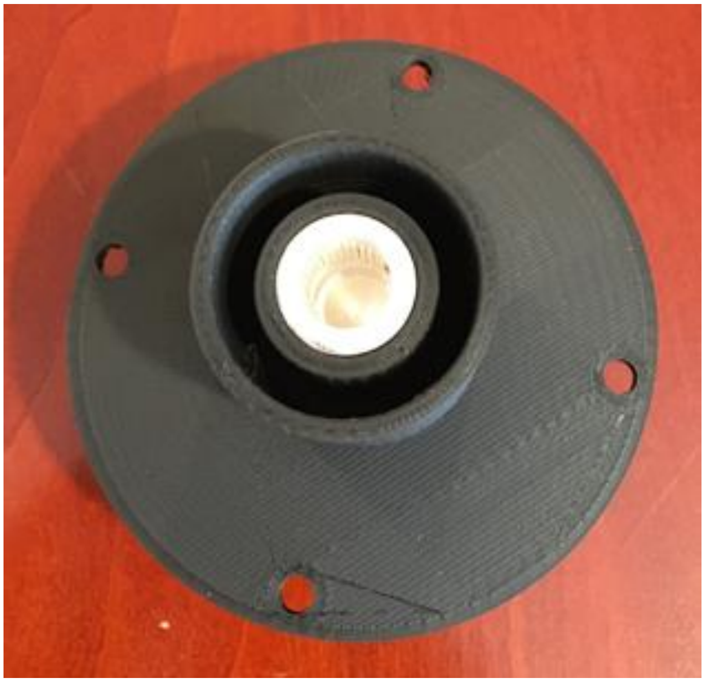


Figure 7-28: 3D printed socket concept design

An area of concern was how difficult it would be to mate the connector. The mating force for the ODU pin and socket was 30 N. The fabricated connector added a negligible amount of extra force to mate. Therefore, additions such as selecting an insulating material which could increase the mating force, decreasing tapering and tolerances between the cylindrical rings to make a more ingress proof mate, or adding an O-ring for ingress protection were viable. The changes could increase connector mating force by 81 N (18.2 lbf) while still being under the required mating force of 111 N specified in section 6.5. A summary of the concept design parameters compared to the requirements are in Table 7-2.

Table 7-2: Design parameters compared to applicable concept design results

Parameter	**Design Condition**	**Concept Design**
Maximum outer diameter (including chassis mating interface)	80.61 mm	80 mm
Maximum outer diameter of the insulation mating interface	44.96 mm	34 mm
Maximum contact mating force	89 N	30 N
Maximum total mating force	111 N	31 N
Creepage distance (mated condition)	60 mm	70.5 mm
Creepage distance (chassis side)	60 mm	65.2 mm
IP protection	44	N/A

8 Conclusions

This thesis identified the constraints on both electrical contacts and insulation requirements necessary to consider in the development of a high-power plug-in connector for the Navy application. An off the shelf electrical contact survey was conducted to identify the state-of-the-art methods and capabilities of high-power electrical contacts. A method to compare dissimilar sized and rated contacts was presented using design graphs and the adoption of four Figure of Merits. Three of the Figure of Merits were chosen to emphasize the specific characteristic according to the physical desired outcome. FOM1 emphasized the contact's current capacity, FOM2 accentuated minimizing resistance, and FOM3 was weighted toward reducing sliding force. FOM4 used the pervious FOMs to create an overall evaluation of the contacts. The Figure of Merits taken with anticipated size at a particular current rating presented a tool by which top preforming contacts and connectors could be differentiated from poor preforming types. The method of using FOMs and design graphs can be used in future selection and design of the shipboard high-power connector.

The insulation requirements were investigated in general and specifically for the naval shipboard environment. Particular attention was paid to US Navy standards and commercial practices in order to define constraints for the connector and insulation. Ambient conditions, ingress protection and creepage distance requirements were identified for the future high-power connector given a range of possible voltage ratings.

A 400-kW (1 kV, 400 A) plug-in connector concept design was developed using a selected contact using the developed FOM process. A compact structure was developed with flexible characteristics so it could be adapted as a starting point for future use. Specific attention was made to the 1 kV value as the associated creepage distance was developed according to that voltage parameter. The connector was designed with an IP 44 rating based on shock and water protection guidelines from the Navy and commercial classification societies.

The developed design was fabricated using a 3D printing process to produce a mock-up used to show the constraints including forces could be achieved in a reasonable sized connector. The design shows it is feasible to make a high-powered plug-in connector suitable for Navy application.

There is still work to be done in order to select, test, and implement a new high-power shipboard electrical connector. The Navy's creepage distance standards need to be updated in order to ensure consistency from lower voltage systems to higher voltage systems, specifically between 1000 V and 1100 V. The Navy's creepage distance guidance does not lend itself to precise design near the ends of the step wise functions laid out in the standards. The FOM processes can be improved by comparing like characteristic adjusted to predicted ambient conditions. The more contacts identified and evaluated will improve the usefulness of FOM4. The processes and constraints identified in this study can inform future work surrounding the connector and power corridor concept.

Bibliography

[1] “Navy Unveils Next-Generation DDG(X) Warship Concept with Hypersonic Missiles, Lasers,” *USNI News*, Jan. 12, 2022. https://news.usni.org/2022/01/12/navy-unveils-next-generation-ddgx-warship-concept-with-hypersonic-missiles-lasers (accessed Feb. 17, 2022).

[2] Capt David Hart, “DDG(X) Program,” presented at the 34th Surface Navy Association National Symposium, Arlington, VA, Jan. 12, 2022. Accessed: Feb. 17, 2022. [Online]. Available: https://s3.documentcloud.org/documents/21177740/sna2022-captdavidhart-ddgx-program.pdf

[3] T. Ericsen, N. Hingorani, and Y. Khersonsky, “PEBB - Power Electronics Building Blocks from Concept to Reality,” in *2006 Record of Conference Papers - IEEE Industry Applications Society 53rd Annual Petroleum and Chemical Industry Conference*, Sep. 2006, pp. 1–7. doi: 10.1109/PCICON.2006.359706.

[4] C. M. Cooke, C. Chryssostomidis, and J. Chalfant, “Modular integrated power corridor,” in *2017 IEEE Electric Ship Technologies Symposium (ESTS)*, Aug. 2017, pp. 91–95. doi: 10.1109/ESTS.2017.8069265.

[5] C. Chryssostomidis and C. M. Cooke, “Space reservation for shipboard electric power distribution systems,” in *2015 IEEE Electric Ship Technologies Symposium (ESTS)*, Jun. 2015, pp. 187–192. doi: 10.1109/ESTS.2015.7157886.

[6] J. del Á. Ferrandis, J. Chalfant, C. M. Cooke, and C. Chryssostomidis, “Design of a Power Corridor Distribution Network,” in *2019 IEEE Electric Ship Technologies Symposium (ESTS)*, Aug. 2019, pp. 284–292. doi: 10.1109/ESTS.2019.8847939.

[7] R. Holm, *Electric Contacts*, Fourth Edition. Springer-Verlag Berlin Heidelberg GmbH, 1967.

[8] M. Braunovic, V. Konchits, and N. Myshkin, *Electrical Contacts: Fundamentals, Applications and Technology*. CRC Press, 2006.

[9] P. Slade, *Electrical Contacts*. New York: Marecl Dekker, Inc, 1999.

[10] Staubli, “MULTILAM Technical Overview,” Switzerland, Brochure, 2017.

[11] Phase 3 Connectors USA, “Powersafe Power Connector Assembly Guide.” Phase 3 USA, Peeksill, NY, 2021.

[12] “DEUTSCH Solid Contacts: CAT-D48-ST273,” *TE Connectivity*. https://www.te.com/usa-en/product-CAT-D48-ST273.html (accessed Jan. 05, 2022).

[13] “5962-203-04141 : DEUTSCH Automotive Terminals,” *TE Connectivity*. https://www.te.com/usa-en/product-5962-203-04141.html (accessed Jan. 05, 2022).

[14] “MIL-DTL-22992-QWLD Connector Catalog.” MILNEC Interconnect Systems, 2021.

[15] ODU USA Inc., “ODU Electrical Contacts,” Camarillo, CA, Catalog, 2021. Accessed: Jun. 30, 2021. [Online]. Available: https://odu-usa.com/engineering-platform/technical-catalogs/#/0/17/9/-1

[16] Smiths Interconnect, “HBB Series: High Power Quick Release Connectors,” Stuart, FL, White Paper, Sep. 2019. Accessed: Jun. 28, 2021. [Online]. Available: https://www.smithsinterconnect.com/products/connectors/high-power/hbb-series/

[17] Smiths Interconnect, “LSH Series: High Power Rack & Panel Connectors,” Stuart, FL, Brochure, 2018. Accessed: Jun. 28, 2021. [Online]. Available: https://www.smithsinterconnect.com/products/connectors/high-power/lsh-series/

[18] Amphenol Industrial, “Radlok IDS-67,” Nogales, AZ, Informational Data Sheet. Accessed: Jun. 25, 2021. [Online]. Available: https://www.amphenol-industrial.com/literature/data-sheets

[19] M. Gatzsche, N. Lücke, S. Großmann, T. Kufner, B. Hagen, and G. Freudiger, “Electric-thermal performance of contact elements in high power plug-in connections,” in *2014 IEEE 60th Holm Conference on Electrical Contacts (Holm)*, Oct. 2014, pp. 1–8. doi: 10.1109/HOLM.2014.7031022.

[20] Spreenb, “Han TC650 female contact 185mm2,” Harting Electric, Engineering Drawing 09110006265, Sep. 2018.

[21] Staubli, “MULTILAM flexo ML-CUX, the high-power contact solution of the future,” Allschwil, Switzerland, Jan. 2018.

[22] Schulzi, “Han TC650 male contact 185mm2,” Harting Electric, Engineering Drawing, Jan. 2015.

[23] Molex, “EXTreme Guardian HD Power Connectors,” Fact Sheet, 2020.

[24] A. Beloufa and M. Amirat, “Design and study of new power connector with parallel contact points,” *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 232, no. 14, pp. 2014–2021, Dec. 2018, doi: 10.1177/0954407018764146.

[25] B. Rubey, A. Patzak, F. Bachheibl, A. Greifelt, and D. Gerling, “Lifetime estimation of a novel high current low resistance single phase plug-in connector for the ISCAD application,” in *2017 Brazilian Power Electronics Conference (COBEP)*, Nov. 2017, pp. 1–5. doi: 10.1109/COBEP.2017.8257246.

[26] AZZ, “HM Contact Systems,” Medway, MA, Brochure. Accessed: Jun. 30, 2021. [Online]. Available: https://www.azz.com/wp-content/uploads/2020/10/HVBS-HM-Contacts.pdf

[27] JAE, “High-current Busbar Connector DW07 Series,” Components Product Information, May 2015. Accessed: Jun. 30, 2021. [Online]. Available: https://www.jae.com/en/connectors/series/detail/id=64183

[28] Staubli, “Round connectors 16BL, Ø 16 mm, insulated,” Switzerland, Brochure, 2020. Accessed: Jun. 23, 2021. [Online]. Available: https://www.staubli.com/en/file/26715.show

[29] Hirose Electric Co, “125A High-Current Waterproof Connectors,” Yokohama, Japan, Brochure, 2019. Accessed: Jun. 28, 2021. [Online]. Available: https://www.hirose.com/product/series/EV1

[30] Harwin, “KA1 SERIES: 8.5mm PITCH HIGH POWER CONNECTORS,” New Albany, Indiana, Component Specification, Jun. 2021.

[31] *In Depth: Loadbreak Probes - Hubbell*, (Dec. 05, 2019). Accessed: Jul. 07, 2021. [Online Video]. Available: https://www.youtube.com/watch?v=gvLPJ2epElA

[32] “Degrees of protection provided by enclosures (IP Code).” IEC 60529, Aug. 2013.

[33] R. Wang, L. Xu, and Y. Zhou, “A Systematic Approach for the Reliability Evaluation of Electric Connector,” *Journal of Electrical and Computer Engineering*, vol. 2021, 2021, doi: http://dx.doi.org.libproxy.mit.edu/10.1155/2021/5514674.

[34] W. P. Yap and S. C. Fok, “A Case-Based Design System for the Conceptual Design of Electrical Connectors,” *The International Journal of Advanced Manufacturing Technology*, vol. 20, no. 11, pp. 787–798, Nov. 2002, doi: 10.1007/s001700200218.

[35] T. C. Galford and G. Purvinis, “A plea for the standardization of underwater connectors,” in *OCEANS’11 MTS/IEEE KONA*, Sep. 2011, pp. 1–6. doi: 10.23919/OCEANS.2011.6107111.

[36] F. Rémouit, P. Ruiz-Minguela, and J. Engström, “Review of Electrical Connectors for Underwater Applications,” *IEEE Journal of Oceanic Engineering*, vol. 43, no. 4, pp. 1037–1047, Oct. 2018, doi: 10.1109/JOE.2017.2745598.

[37] T. Schilla and M. Schuster, “Simplify your HV-harness — Uniform high current connectors for batteries, inverters and motors in heavy-duty vehicles and passenger cars,” in *2010 Emobility - Electrical Power Train*, Nov. 2010, pp. 1–6. doi: 10.1109/EMOBILITY.2010.5668059.

[38] A. Altinisik and U. Yildirim, “Failure prediction in electrical connector assembly: a case in automotive assembly process,” *Assembly Automation*, vol. 40, no. 6, pp. 881–893, Jan. 2020, doi: 10.1108/AA-06-2020-0077.

[39] A. R. Susoeff, R. S. Hawke, and K. S. Leighton, “A mechanical connector design for high-current, high-Coulomb pulsed power systems,” *IEEE Transactions on Magnetics*, vol. 29, no. 1, pp. 1070–1075, Jan. 1993, doi: 10.1109/20.195729.

[40] R. P. Flatt, “High Voltage, High Current Connectors Through 1250a, 36 kV A New Approach,” in *1979 7th IEEE/PES Transmission and Distribution Conference and Exposition*, Apr. 1979, pp. 308–309. doi: 10.1109/TDC.1979.712680.

[41] K. Yasuoka, Y. Yamada, and M. Chen, “Contact Resistance and Arc-free Commutation Current of Tungsten-clad Copper Contacts for a Hybrid DC Switch,” in *2019 IEEE Holm Conference on Electrical Contacts*, Sep. 2019, pp. 359–362. doi: 10.1109/HOLM.2019.8923889.

[42] S. V. Angadi, R. L. Jackson, V. Pujar, and M. R. Tushar, “A Comprehensive Review of the Finite Element Modeling of Electrical Connectors Including Their Contacts,” *IEEE Transactions*

on Components, Packaging and Manufacturing Technology, vol. 10, no. 5, pp. 836–844, May 2020, doi: 10.1109/TCPMT.2020.2982207.

[43] J. R. Polchow *et al.*, “A Multi-Physics Finite Element Analysis of Round Pin High Power Connectors,” in *2010 Proceedings of the 56th IEEE Holm Conference on Electrical Contacts*, Oct. 2010, pp. 1–9. doi: 10.1109/HOLM.2010.5619567.

[44] N. Zhu, G. Zhai, and Z. Guo, “Research on Contact Reliability Design of Electrical Connector Contact,” in *2019 International Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering (QR2MSE)*, Aug. 2019, pp. 155–160. doi: 10.1109/QR2MSE46217.2019.9021171.

[45] L. Y. Yao, “Research on the key influence factors of power connector design,” Master Thesis, Beijing University of Posts and Telecommunications, Beijing, China, 2018.

[46] Y. Li, F. Zhu, Y. Chen, K. Duan, K. Tang, and S. Liu, “Analysis of insertion force of electric connector based on FEM,” in *Proceedings of the 21th International Symposium on the Physical and Failure Analysis of Integrated Circuits (IPFA)*, Jun. 2014, pp. 195–198. doi: 10.1109/IPFA.2014.6898160.

[47] T. Israel, S. Schlegel, S. Großmann, T. Kufner, and G. Freudiger, “Modelling of Transient Heating and Softening Behaviour of Contact Points During Current Pulses and Short Circuits,” in *2019 IEEE Holm Conference on Electrical Contacts*, Sep. 2019, pp. 9–18. doi: 10.1109/HOLM.2019.8923941.

[48] M. Blauth, F. Berger, and J. Song, “Optimization of the Number of Contact Springs in a Connector by means of Analytical and Numerical Analysis,” in *ICEC 2014; The 27th International Conference on Electrical Contacts*, Jun. 2014, pp. 1–6.

[49] Q. Jin, J. Gao, L. Bi, and Y. Zhou, “The Impact of Contact Pressure on Passive Intermodulation in Coaxial Connectors,” *IEEE Microwave and Wireless Components Letters*, vol. 30, no. 2, pp. 177–180, Feb. 2020, doi: 10.1109/LMWC.2019.2957983.

[50] A. Beloufa, “Influence of shapes, contact forces and high copper alloys on the contact resistance and temperature,” *Proceedings of the 2nd WSEAS International Conference on ENGINEERING MECHANICS, STRUCTURES and ENGINEERING GEOLOGY*, 2009.

[51] A. K. Bhargava, “A new high strength copper-tin-zinc alloy for connectors and other conductive springs,” in *2000 Proceedings. 50th Electronic Components and Technology Conference (Cat. No.00CH37070)*, May 2000, pp. 1139–1146. doi: 10.1109/ECTC.2000.853315.

[52] M. Buggy and C. Conlon, “Material selection in the design of electrical connectors,” *Journal of Materials Processing Technology*, vol. 153–154, pp. 213–218, Nov. 2004, doi: 10.1016/j.jmatprotec.2004.04.209.

[53] N. Lücke, S. Grossmann, H. Löbl, T. Ledermann, and G. Freudiger, “Long-Term Behaviour of Plug-in Connectors with Copper Beryllium Contact Lamellas Depending on Stress Relaxation,” in *2010 Proceedings of the 56th IEEE Holm Conference on Electrical Contacts*, Oct. 2010, pp. 1–6. doi: 10.1109/HOLM.2010.5619471.

[54] M. Antler, “Gold plated contacts: effect of thermal aging on contact resistance,” in *Electrical Contacts - 1997 Proceedings of the Forty-Third IEEE Holm Conference on Electrical Contacts*, Oct. 1997, pp. 121–131. doi: 10.1109/HOLM.1997.638004.

[55] L. Revay, “Surface accumulation rate of diffusing species on thin gold electroplates,” in *Electrical Contacts - 1991 Proceedings of the Thirty-Seventh IEEE HOLM Conference on Electrical Contacts*, Oct. 1991, pp. 193–198. doi: 10.1109/HOLM.1991.170824.

[56] M. P. Larsson, “Improved contact resistance stability in a MEMS separable electrical connector,” in *Microelectronics: Design, Technology, and Packaging II*, Jan. 2006, vol. 6035, p. 60350V. doi: 10.1117/12.638330.

[57] Y. Ren, Q. Feng, T. Ye, and B. Sun, “A Novel Model of Reliability Assessment for Circular Electrical Connectors,” *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 5, no. 6, pp. 755–761, Jun. 2015, doi: 10.1109/TCPMT.2015.2419222.

[58] R. Abdi, E. Carvou, and N. Benjemaa, “Electrical resistance change of automotive connectors submitted to vibrations and temperature,” Sep. 2015, pp. 1910–1913. doi: 10.1109/ECCE.2015.7309929.

[59] M. Oberst, S. Schlegel, S. Großmann, H. Willing, and R. Freudenberger, “Impact of the Formation of Intermetallic Compounds in Current-Carrying Connections,” *IEEE Transactions on Device and Materials Reliability*, vol. 20, no. 1, pp. 157–166, Mar. 2020, doi: 10.1109/TDMR.2020.2971055.

[60] Z. Chongyang, F. Qiang, and S. Bo, “Lifetime prediction for electrical connector under the action of random vibration loading,” in *Proceedings of the IEEE 2012 Prognostics and System Health Management Conference (PHM-2012 Beijing)*, May 2012, pp. 1–5. doi: 10.1109/PHM.2012.6228872.

[61] S. M. Glista, W. F. Burns, and B. Lessard, “F-22 Lessons Learned: Line Replaceable Module (LRM) Electrical Connector—An Investigation of Vibration-Induced Contact Wear and Electro Static Discharge Hardening,” Jul. 2010, pp. 327–340. doi: 10.1115/IMECE2009-10489.

[62] A. G. Day and D. J. Stonard, “Creepage and Clearance Distances in Electrical Equipment for Shipboard Use,” *IEEE Transactions on Electrical Insulation*, vol. EI-12, no. 3, pp. 191–199, Jun. 1977, doi: 10.1109/TEI.1977.298019.

[63] T. Damle *et al.*, “Experimental setup to evaluate creepage distance requirements for shipboard power systems,” in *2019 IEEE Electric Ship Technologies Symposium (ESTS)*, Aug. 2019, pp. 317–323. doi: 10.1109/ESTS.2019.8847827.

[64] S. S. El-Dessouky and F. M. H. Youssef, “Factors affecting creepage and clearance distances of polymer insulators in coastal and marine electrical equipment,” in *6th International Symposium on Electrets,(ISE 6) Proceedings.*, Sep. 1988, pp. 354–358. doi: 10.1109/ISE.1988.38579.

[65] “Connectors for electronic equipment - Tests and measurements,” International Electrotechnical Commission, IEC 60512-5-2, Feb. 2002.

[66] “Radsok High Power Connectors,” Amphenol Industrial, Catalog. Accessed: Nov. 30, 2021. [Online]. Available: https://www.amphenol-sine.com/Radsok-High-Power-Connectors-Catalog_p_7003.html

[67] “Insulation Coordination Including Clearances and Creepage Distances for Electrical Equipment,” Underwriters Laboratories Inc., Standard for Safety UL 840, Sep. 2000.

[68] P. von Schau and W. H. Middendorf, “An International Research Project to Determine New Dimensioning Crules for Creepage Distances,” *IEEE Transactions on Electrical Insulation*, vol. EI-18, no. 2, pp. 158–162, Apr. 1983, doi: 10.1109/TEI.1983.298661.

[69] “Standard Test Method for Comparative Tracking Index of Electrical Insulating Materials,” ASTM, Standard ASTM D3638-21e1.

[70] “Method for the determination of the proof and the comparative tracking indices of solid insulating materials,” International Standard IEC 60112:2020, Oct. 2020.

[71] “Insulation coordination for equipment within low-voltage supply systems - Part 1: Principles, requirements and tests,” International Electrotechnical Commission, International Standard IEC 60664-1:2020, May 2020.

[72] “Connectors - Safety Requirements and Tests,” International Electrotechnical Commission, IEC Standard 61984, Oct. 2008.

[73] “Detail Specification Electric Power Equipment, Basic Requirements For,” Department of Defense, MIL-DTL-917F, Aug. 2014.

[74] “Military Standard, Definitions of and Basic Requirements for Enclosures for Electric and Electronic Equipment,” Department of Defense, MIL-STD-108E, Aug. 1966.

[75] “Unified requirements for systems with voltages above 1 kV up to 15 kV,” International Association of Classification Societies, IACS UR E11, Feb. 2021.

[76] “Electrical installations in ships – Part 503: Special features – AC supply systems with voltages in the range of above 1 kV up to and including 15 kV,” International Electrotechnical Commission, International Standard 60092–503, Jun. 2007.

[77] “Rules for Classification: Naval Vessels, Part 3 Surface Ships, Chapter 3 Electrical Installations,” DNV GL, Jul. 2019.

[78] “IEEE Standard for Separable Insulated Connector Systems for Power Distribution Systems Rated 2.5 kV through 35 kV,” *IEEE Std 386-2016 (Revision of IEEE Std 386-2006)*, pp. 1–81, Oct. 2016, doi: 10.1109/IEEESTD.2016.7592838.

[79] T. L. Ong, T. C. Cheng, and N. G. Hingorani, “Survey of Creepage Distances and Clearances in HVDC Converter Stations,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-104, no. 8, pp. 2255–2265, Aug. 1985, doi: 10.1109/TPAS.1985.318806.

[80] “Rules for Building and Classing Marine Vessels, Part 4, Vessel Systems and Machinery,” ABS, Jul. 2021.

[81] "Electrical Connectors, Plug-in sockets and associated hardware, selection and use of," Department of Defense, Department of Defense Standard Practice MIL-STD-1353C, Feb. 2014.

[82] "Test Methods for Electrical Connectors," MIL-STD-1344, Oct. 2004.

[83] "Electrical Connector/Socket Test Procedures Including Environmental Classifications," EIA Standard, EIA-364G, Jul. 2021.

[84] "Connectors, Electrical, Circular, Miniature, High Density, Quick Disconnect (Bayonet, Threaded, And Breech Coupling), Environment Resistant, Removable Crimp And Hermetic Solder Contacts, General Specification For," Department of Defense, Detail Specification MIL-DTL-38999L, May 2008.

[85] "Encyclopedia of Marine and Energy Technology," *Wartsila.com*. https://www.wartsila.com/encyclopedia (accessed Feb. 03, 2022).

[86] Petty Officer 3rd Class Andrew Langholf, *211111-N-FA490-1139*. 2021. Accessed: Feb. 03, 2022. [Photograph]. Available: https://www.navy.mil/Resources/Photo-Gallery/igphoto/2002892972/

[87] "Rules for the Classification of Naval Ships, Part C-Machinery, Systems and Fire protection," Bureau Veritas, Oct. 2020.

[88] "Detail Specification Enclosures for electric and electronic equipment, Naval Shipboard," Department of Defense, MIL-DTL-2036E, Feb. 2014.

[89] "Insert Arrangements for SAE-AS50151, MIL-DTL-22992, MIL-DTL-83723 and SAE-AS95234 Circular Electrical Connectors," Department of Defense, Interface Standard MIL-STD-1651B, Sep. 2020.

[90] "Connectors, plug and receptacles, electrical, waterproof, quick disconnect, heavy duty type, general specification for," Department of Defense, MIL-DTL-22992H, Mar. 2021.

[91] "ACA-B and GT Series: Reverse Bayonet Coupling Connectors," Amphenol Industrial, Sidney, New York, Catalog. Accessed: Feb. 04, 2022. [Online]. Available: https://www.amphenol-industrial.com/c/images/catalogs/ACA-B%20-%20GT%20Catalog.pdf

[92] “Connectors, Electrical, Circular Threaded, AN Type, General Specification for,” SAE International, AS50151E, Jun. 2020.

[93] C. C. for O. H. and S. Government of Canada, “Pushing & Pulling - General : OSH Answers,” Feb. 07, 2022. https://www.ccohs.ca/oshanswers/ergonomics/push1.html (accessed Feb. 07, 2022).

[94] “RobiFix: Flat primary circuit connecotrs | Welding automation,” Staubli, Catalog, Mar. 2021. Accessed: Jun. 15, 2021. [Online]. Available: https://www.staubli.com/en-us/electrical-connectors/spot-welding-connectors/primary-circuit-flat/

[95] “S250-PCB-KIT, S300-PCB-KIT, PCB Mount Assembly,” International Hydraulics, Inc., Drawing 5300 (250) PCB Mount Assembly, Oct. 2011.

[96] “Dielectric Strength: Units, Test Methods & Material Table.” https://omnexus.specialchem.com/polymer-properties/properties/dielectric-strength (accessed Feb. 03, 2022).

Appendix A

List of commercial off the shelf products and information sources.

Brand	Connector	Date accessed	Website Information
Amphenol	Radlok	6/14/2021	https://www.amphenol-industrial.com/radlok
Amphenol	Radsok	6/14/2021	https://www.amphenol-sine.com/radsok
AZZ	HM Contact System (HM-38)	6/30/2021	https://www.azz.com/hm-contact-systems/
AZZ	HM Contact System (HM-95)	6/30/2021	https://www.azz.com/hm-contact-systems/
Deutsch	DTHD	6/21/2021	https://www.deutschconnectors.com.au/deutsch-dthd-connector-kit-100a-1-pole.html
Eaton	Roughneck	6/22/2021	https://www.eaton.com/us/en-us/catalog/wiring-devices-and-connectivity-crouse-hinds/roughneck-single-pole-high-amperage-plugs-and-connectors.html
Eaton	Rough-lok	6/22/2021	https://www.eaton.com/us/en-us/catalog/wiring-devices-and-connectivity-crouse-hinds/rough-lok-single-pole-high-amperage-plugs-and-connectors.html
Eaton	Cam-lok	6/22/2021	https://www.eaton.com/us/en-us/catalog/wiring-devices-and-connectivity-crouse-hinds/cam-lok-j-series-single-pole-plugs-and-receptacles.html
Harting	Han S	6/14/2021	https://www.harting.com/US/en/connector-battery-storage?matchtype=e&sncid=13&utm_source=google&utm_medium=cpc&utm_campaign=industrial_connectors_sn&adgroup=hans_s&gclid=Cj0KCQjw_dWGBhDAARIsAMcYuJw6CtbaJXvKDFtpT9e-7En18oVAfJlF8n_togJbVi7etDDPjpU98ccaAp8LEALw_wcB
Harwin	Kona	6/14/2021	https://www.harwin.com/kona-connectors/
Hirose	PS3C Series	6/28/2021	https://www.hirose.com/en/product/series/PS3C
Hirose	EM30MSD Series	6/28/2021	https://www.hirose.com/en/product/series/EM30MSD
Hirose	EV1	6/28/2021	https://www.hirose.com/en/product/series/EV1
Hubbell	Load Break	7/7/2021	https://www.hubbell.com/hubbellpowersystems/en/Products/Power-Utilities/Underground-Separable-Connectors/Loadbreak-Elbows/15-kV-Load-Break-Elbow-w-Bimetal-Contact/p/1526575
Hubbell	PowerEX	7/14/2021	https://www.hubbell.com/hubbell/en/Products/Electrical-Electronic/Electrical-Connectors/Hazardous-Location/PowerEx/p/2147034
ITT Cannon	Powerlock	6/15/2021	https://www.ittcannon.com/products/powerlock/
ITT Cannon	Snaplock	6/15/2021	https://www.ittcannon.com/products/snaplock/
ITT Veam	VSC	6/15/2021	https://www.ittcannon.com/products/vsc/
JAE	DW Series	6/30/2021	https://www.jae.com/en/connectors/series/detail/id=64181&type_code=T1120
JAE	JK06 Series	6/30/2021	https://www.jae.com/en/connectors/series/detail/id=64262&application_code=A1060&application_detail_code=A1060-AS010
JAE	KW04 Series	6/30/2021	https://www.jae.com/en/connectors/series/detail/id=91783&type_code=T1130
Molex	Brad Quick-Change Connectors	6/21/2021	https://www.molex.com/molex/products/part-detail/receptacles/1300030048
Molex	EXTreme PowerMass High-Current Connectors	6/21/2021	https://www.molex.com/molex/products/part-detail/pcb_headers/0755565101
Molex	EXTreme Guardian System	6/21/2021	https://www.molex.com/molex/products/part-detail/pcb_headers/2141130011
ODU	Springtac	6/30/2021	https://odu-usa.com/products/electrical-contacts/odu-lamtac/
ODU	Lamtac	6/30/2021	https://odu-usa.com/products/electrical-contacts/odu-springtac/
ODU	Turntac	6/30/2021	https://odu-usa.com/products/electrical-contacts/odu-turntac/
Phase 3	Powersafe	6/21/2021	https://usa.p3connectors.com/single-pole-connector/
Phase 3	Showsafe	6/21/2021	https://usa.p3connectors.com/showsafe-connectors/
Smiths Interconnect	HBB Series	6/28/2021	https://www.smithsinterconnect.com/products/connectors/high-power/hbb-series/
Smiths Interconnect	Transformer Series	7/7/2021	https://www.smithsinterconnect.com/products/connectors/high-power/transformer-series/
Smiths Interconnect	LSH Series	6/28/2021	https://www.smithsinterconnect.com/products/connectors/high-power/lsh-series/
Smiths Interconnect	Hyperboloid Technology	7/7/2021	https://www.smithsinterconnect.com/library/technical-library/technology/hyperboloid-technology/
Smiths Interconnect	Tortac Technology	7/7/2021	https://www.smithsinterconnect.com/products/connectors/contact-technologies/tortac%C2%AE-contact/
Staubli	Single-pole round connector 16BL	6/23/2021	https://www.staubli.com/en/electrical-connectors/single-pole/round-insulated-connectors-10-21-mm/
Staubli	Single-pole round connector 21BV	6/23/2021	https://www.staubli.com/en/electrical-connectors/single-pole/round-insulated-connectors-10-21-mm/
Staubli	Robifix	6/15/2021	https://www.staubli.com/en-us/electrical-connectors/spot-welding-connectors/primary-circuit-flat/
Staubli	Multilam Plugs	6/15/2021	https://www.staubli.com/en-us/electrical-connectors/single-pole/multilam-plug-connectors/
Staubli	Performore	6/15/2021	https://www.staubli.com/en-us/electrical-connectors/multi-pole-connectors/e-mobility-connection-solutions/performore/
Staubli	Multilam Flexo	7/23/2021	https://www.staubli.com/en-us/electrical-connectors/multilam-technology/multilam-flexo/
Staubli	Multilam Technology	7/14/2021	https://www.staubli.com/us/en/electrical-connectors/products/multilam-products-and-technology/multilam-torsio.html
ZZDQ	Ceeform	6/15/2021	https://www.ceesockets.com/knowledge/what-is-ceeform-cee-form-fully-explained/

Appendix B

Multilam Design Summary Examples

Type	# of louvers	Round Contact: diameter (mm)	Current Capacity of contact (A)	Resistance of contact (μΩ)	Sliding force of contact (N)	Power dissipation (W)
400 A						
F: LAII/0.20	18	8.60	414	19.44	100.8	3.11
C: LAIA/0.25	14	11.15	406	25.00	98	4.00
G: LA-CU/0.15-0.5	11	12.26	440	27.27	26.95	4.36
800 A						
A: LA0/0.30	19	30.25	817	15.26	113.05	9.77
C+: LAIA/0.30	23	18.31	805	13.04	261.625	8.35
F: LAII/0.20	35	16.72	805	10.00	196	6.40
G: LA-CU/0.15-0.5	20	22.29	800	15.00	49	9.60
1000 A						
A: LA0/0.30	24	38.22	1032	12.08	142.8	12.08
C+: LAIA/0.40	27	21.50	1026	10.37	642.6	10.37
E+: LAIB/0.25	35	27.87	1015	10.00	245	10.00
G: LA-CU/0.15-0.5	25	27.87	1000	12.00	61.25	12.00
1200 A						
A: LA0/0.30	28	44.59	1204	10.36	166.6	14.91
B: LA0-G/0.25	32	25.48	1216	9.38	100.8	13.50
C+: LAIA/0.40	32	25.48	1216	8.75	761.6	12.60
C+: LAIA/0.50	28	22.29	1204	8.93	1029	12.86
E: LAIB/0.30	35	27.87	1225	8.57	398.125	12.34
E+: LAIB/0.25	42	33.44	1218	8.33	294	12.00
E+: LAIB/0.20	43	34.24	1204	9.30	225.75	13.40
G: LA-CU/0.15-0.5	30	33.44	1200	10.00	73.5	102.40
1600 A						
A: LA0/0.30	38	60.51	1634	7.63	226.1	19.54
B: LA0-G/0.25	43	34.24	1634	6.98	135.45	17.86
C+: LAIA/0.40	43	34.24	1634	6.51	1023.4	16.67
C+: LAIA/0.50	38	30.25	1634	6.58	1396.5	16.84
E: LAIB/0.30	46	36.62	1610	6.52	523.25	16.70
E+: LAIB/0.25	56	44.59	1624	6.25	392	16.00
G: LA-CU/0.15-0.5	40	44.59	1600	7.50	98	19.20
H: LA-CUT/0.25	40	50.96	1600	10.00	140	25.60
I: LA-CUD/0.15	32	25.48	1600	10.31	89.6	26.40
3200 A						

B: LA0-G/0.25	85	67.68	3230	3.53	267.75	36.14
C+: LAIA/0.40	85	67.68	3230	3.29	2023	33.73
C+: LAIA/0.50	75	59.71	3225	3.33	2756.25	34.13
G: LA-CU/0.15-0.5	80	89.17	3200	3.75	196	38.40
I: LA-CUD/0.15	64	50.96	3200	5.16	179.2	52.80

Appendix C

Consolidated DNV and ABS ingress protection tables

Equipment up to 1000 V

Condition in location	Example of location	Switchboard, control gear, motor starters	Generators	Motors	Transformers	Lighting Fixtures
Danger of touching live parts only	Dry accommodation spaces, dry control rooms	IP 20	X	IP20	IP20	IP20
Danger of dripping liquid and/or moderate mechanical damage	Control rooms, wheel-house, radio room	IP22	X	IP22	IP22	IP22
	Engine and boiler rooms above floor	IP22	IP22	IP22	IP22	IP22
	Steering gear rooms	IP22	IP22	IP22	IP22	IP22
	Emergency machinery rooms	IP22	IP22	IP22	IP22	IP22
	General storerooms	IP22	X	IP22	IP22	IP22
	Pantries	IP22	X	IP22	IP22	IP22
	Provision rooms	IP22	X	IP22	IP22	IP22
	Ventilation ducts	X	X	IP22	X	X
Increased danger of liquid and/or mechanical damage	Bathrooms and/or showers	X	X	X	X	IP34
	Engine and boiler rooms below floor	X	X	IP44	X	IP34
	Closed fuel oil separator rooms	IP44	X	IP44	IP44	IP34
	Closed lubricating oil separator rooms	IP44	X	IP44	IP44	IP34
Increased danger of liquid and mechanical damage	Ballast pump rooms	IP44	X	IP44	IP44	IP34
	Refrigerated rooms	X	X	IP44	X	IP34
	Galleys and laundries	IP44	X	IP44	IP44	IP34
Danger of liquid spraying, presence of cargo dust, serious mechanical damage, aggressive fumes	Shaft or pipe tunnels in double bottom	IP55	X	IP55	IP55	IP55
	Holds for general cargo	X	X	IP55	X	IP55
	Ventilation trunks	X	X	IP55	X	X
Danger of liquid in massive quantities	Open decks	IP56	X	IP56	X	IP55

Equipment up to 1000 V continued

Condition in location	Example of location	Heating appliances	Cooking appliances	Socket outlets	Accessories (e.g. switches, connection boxes)
Danger of touching live parts only	Dry accommodation spaces, dry control rooms	IP20	IP20	IP20	IP20
Danger of dripping liquid and/or moderate mechanical damage	Control rooms, wheel-house, radio room	IP22	IP22	IP22	IP22
	Engine and boiler rooms above floor	IP22	IP22	IP44	IP44
	Steering gear rooms	IP22	X	IP44	IP44
	Emergency machinery rooms	IP22	X	IP44	IP44
	General storerooms	IP22	X	IP22	IP44
	Pantries	IP22	IP22	IP44	IP44
	Provision rooms	IP22	X	IP44	IP44
	Ventilation ducts	X	X	X	X
Increased danger of liquid and/or mechanical damage	Bathrooms and/or showers	IP44	X	IP55	IP55
	Engine and boiler rooms below floor	IP44	X	X	IP55
	Closed fuel oil separator rooms	IP44	X	X	IP55
	Closed lubricating oil separator rooms	IP44	X	X	IP55
Increased danger of liquid and mechanical damage	Ballast pump rooms	IP44	X	IP55	IP55
	Refrigerated rooms	IP44	X	IP55	IP55
	Galleys and laundries	IP44	IP44	IP44	IP44
Danger of liquid spraying, presence of cargo dust, serious mechanical damage, aggressive fumes	Shaft or pipe tunnels in double bottom	IP55	X	IP56	IP56
	Holds for general cargo	IP55	X	IP56	IP56
	Ventilation trunks	X	X	X	X
Danger of liquid in massive quantities	Open decks	IP56	X	IP56	IP56

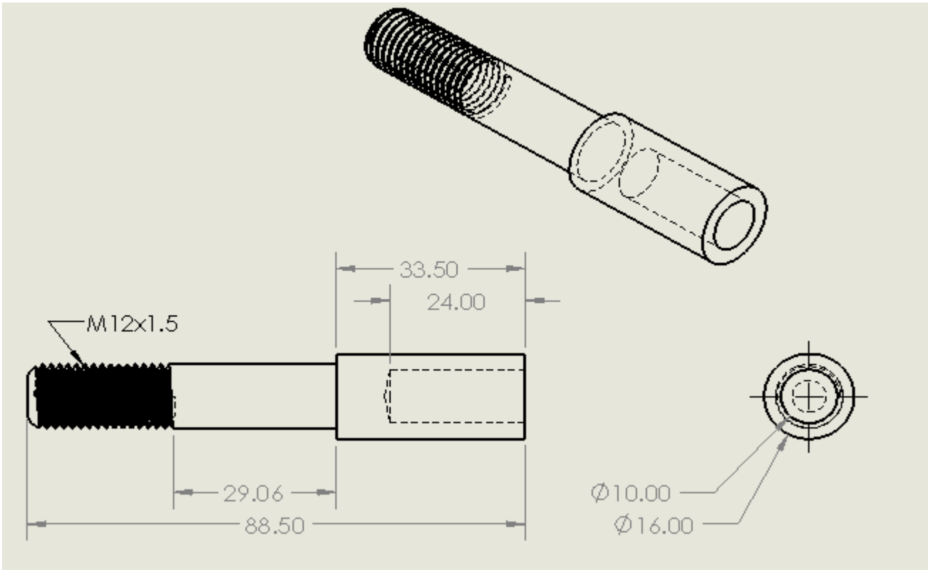
Equipment above 1000 V

Condition in location	Example of location	Switchboards, Distribution Boards, Motor Control Centers and Controller	Generators	Motors	Transformers, Converters	Electrical Machinery Terminal, Junction, Connection Boxes
Danger of touching live parts only	Dry control rooms Authorized Personnel Only	IP32	X	X	IP23	IP44
	Dry Control Rooms	IP42	X	X	IP44	IP44
Danger of dripping liquid and/or moderate mechanical damage	Control rooms Authorized Personnel Only	IP32	X	X	IP23	IP44
	Control Rooms	IP42	IP23	X	IP44	IP44
	Above floor plates in machinery spaces Authorized Personnel Only	IP32	IP23	IP23	IP23	IP44
	Above floor plates in machinery spaces	IP42	IP23	IP43	IP44	IP44
	Emergency machinery rooms Authorized Personnel Only	IP32	IP23	IP23	IP23	IP44
	Emergency machinery rooms	IP42	IP23	IP43	IP44	IP44
Increased danger of liquid and/or mechanical damage	Below floor plates in machinery spaces Authorized Personnel Only	X	X	X	X	IP44
	Below floor plates in machinery spaces	X	X	X	X	IP44
Increased danger of liquid and mechanical damage	Ballast pump roomsAuthorized Personnel Only	IP44	X	IP44	IP44	IP44
	Ballast pump rooms	IP44	X	IP44	IP44	IP44
Danger of liquid spray presence of cargo dust, serious mechanical damage, and/or aggressive fumes	Holds for general cargo	X	X	X	X	IP55
Not exposed to seas	Open decks	X	IP56	IP56	IP56	IP56

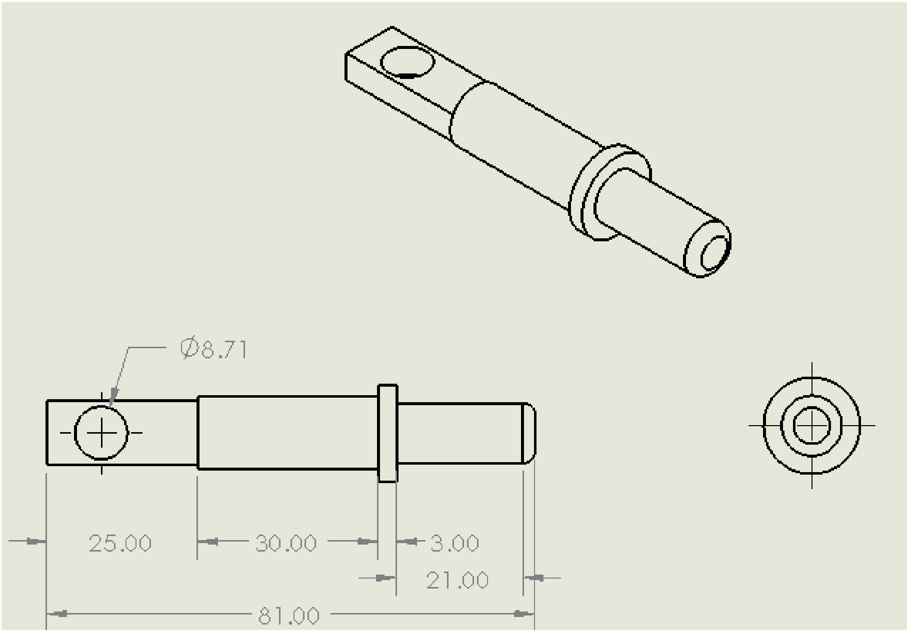
Appendix D

Threaded and Lugged configurations

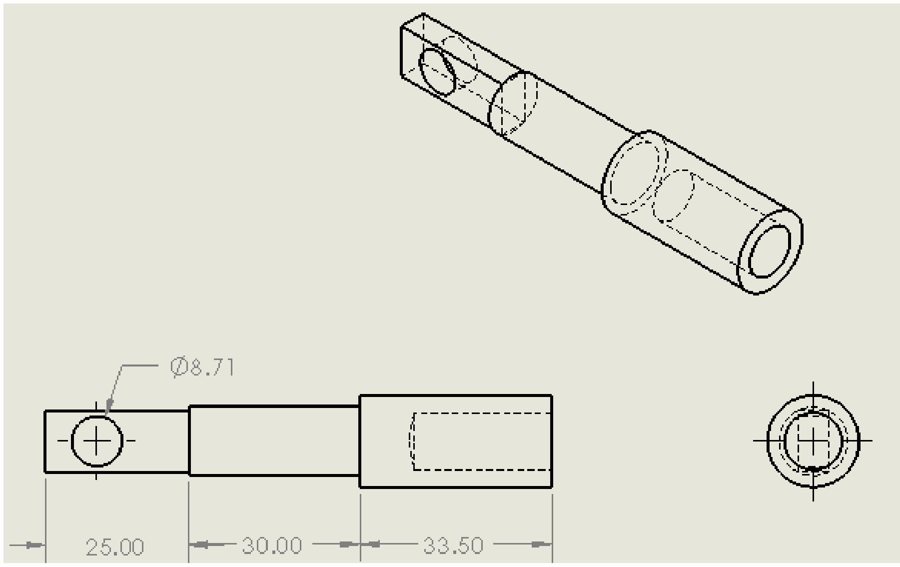
Threaded socket



Lugged pin

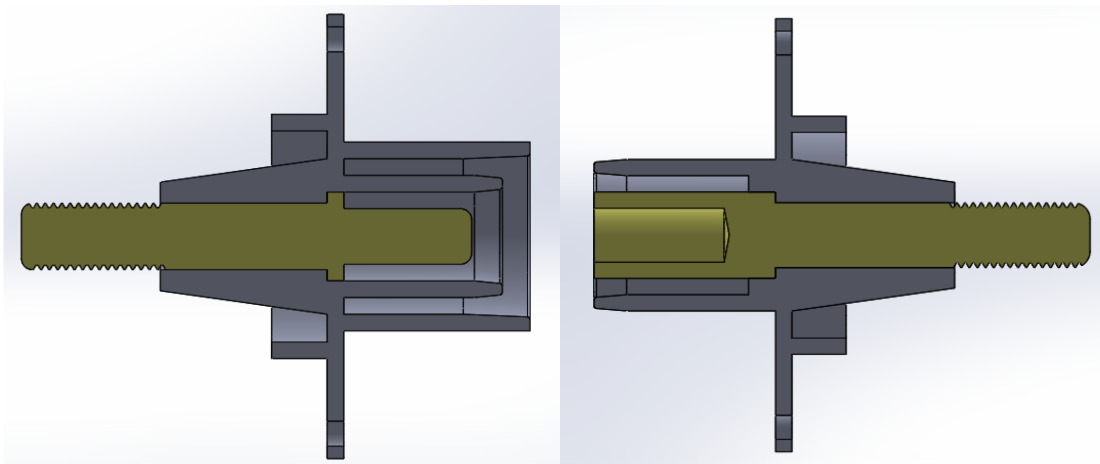


Lugged socket



Appendix E

Initially, the concept design was fabricated with zero tolerance between creepage cylinders. Only the first 6 mm of the cylinders were tapered to allow for some misalignment. Additionally, the pin was surrounded by two creepage cylinders and the socket was surrounded by one three millimeters away. The below figures show this configuration.



This configuration resulted in three friction surfaces: outside of the metal socket against the inner cylinder, inner cylinder against the middle cylinder, and the outer cylinder against the middle cylinder. As a result of the three friction surfaces, tight tolerances, and short taper a marked increase in the full connector mating force compared to the mating force of the pin and socket alone. The tight tolerances created a tight seal which created a problem when un-mating. When the connector was mated, all the air in the cylinders was forced out. As a result, a vacuum formed and would not allow the connectors to be disconnected without first breaking the vacuum. It required the connectors to be twisted in opposite directions as they were pulled apart. The mating force was 124 N (28 lbf).

To decrease the mating force and resolve the vacuum problem greater taper was given to the creepage cylinders. The taper was increased to run the full length of each cylinder. The sliding surfaces were reduced from three to two by switching the socket and pin relative to the insulator design. In the redesign the socket was on the side with two creepage cylinders. It was permanently press fitted into the insulator thereby eliminating one friction surface. The amount of taper in relation to acceptable force and ingress protection benefits were not investigated in this thesis and are left for future work.