QwikConnect®

GLENAIR • JANUARY 2025 • VOLUME 29 • NUMBER 1

Thermal Management in Electrical Wire Interconnect Systems

Glenair®

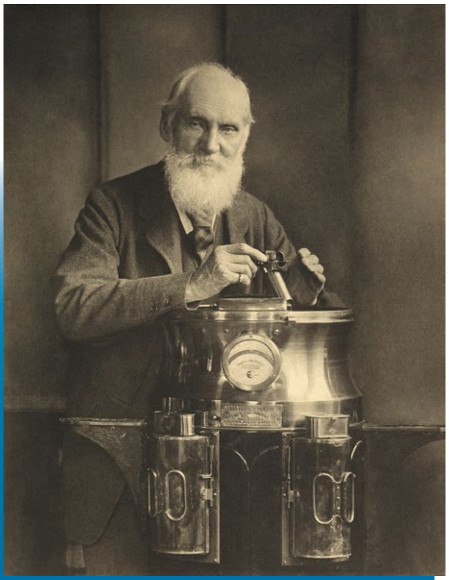
ThermaRex™

CRYO • HIGH TEMP • ULTRA HIGH-TEMP

Thermal Management in Electrical Wire Interconnect Systems

For an aircraft at high altitude, ambient temperature can reach **lows of -65°C**, while the temperature next to to engines can get as **high as +200°C**.

This special edition of QwikConnect details Glenair's innovative approach to product design and material selection for extreme thermal management in electrical wire interconnect systems. We'll discuss thermal resistance in conventional mil-spec style interconnects, as well as higher and lower temperature performing products from our signature ThermaRex family of extreme-temperature interconnect solutions.



Sir William Thomson, Baron Kelvin
1824 - 1907. While the existence of a coldest possible temperature—absolute zero—was known before his work, Kelvin determined its correct value as −273.15° Celsius or −459.67° Fahrenheit. Absolute temperatures are stated in units of Kelvin in Lord Kelvin's honor.

Before we begin, let's define exactly what is meant by extreme temperatures in harsh-environment interconnects and cable assemblies.

The two extremes referenced in this context are for cryogenic applications—or anything colder than -150°C, or 123 Kelvin, which defines the upper cryogenic limit for functional interconnects for today's application requirements. Ultra low-temperature cryo applications go down as far as -269°C/ 4 Kelvin, and cryo sensor applications can approach absolute zero.

The Kelvin scale establishes an absolute thermometric scale and is the primary unit of measurement in the physical sciences. Absolute zero Kelvin is equivalent to −273.15 °C (−459.67 °F) and is the temperature where no further energy can be extracted from the system.

At the other end of the spectrum, temperatures in the range of plus 300°C are at the lower end of what is considered the high-temperature application environment. Requirements for ultra-high temperature interconnects and cable assemblies extend to temperatures as high as 600°C.

It's important to note the difference between rated operating temperature versus the ability of a part or assembly to survive excursions to higher and lower temperatures. In addition, it is also critical to understand that the source of extreme temperatures can be both internal to the system, i.e., heat generated by electromagnetic activity within a cable or connector, and external environmental sources of heat, such as proximity to an aircraft engine.

Let's look at some broad categories of standard interconnect product and their rated operating temperature ranges.

In a typical aerospace application, at high altitude, the ambient negative temperature can reach lows of -65°C, while proximity to engines can result in exposure to high temperatures up to +200°C. The broad range of mil-spec connectors, such as D38999, and signature Glenair products such as Series 806, are designed and fabricated to function safely and reliably within this temperature range.

But what would be the consequences of exceeding these rated operating temperatures? Standard-environment insulator materials for example—when exposed to higher-rated temperatures—can experience burning, melting, cracking, and reduced insulation resistance. metallic contacts such as plated BeCu socketswould likely experience stress relaxation and strength reduction due to a condition called over-aging at temperatures above +200°C. (See sidebar for more details on stress relaxation in metal materials.)

Beryllium copper material is typically used in standard-environment socket contacts. This material experiences stress relaxation (loses its spring force) at temperatures higher than +200°C, resulting in reduced contact engagement and separation forces that can increase contact resistance.

CRYOGENICS IN SPACE

Cryogenic temperatures, which generally refer to temperatures below -150°C (123 K), play a crucial role in space applications across various domains, from satellite instrumentation to scientific research and space exploration. In the vacuum of space, temperatures can fluctuate widely, often reaching cryogenic levels, especially in shaded areas where there is no exposure to sunlight. These extreme cold conditions present unique challenges and opportunities in designing systems for space, particularly for the management of sensitive equipment, energy resources, and thermal stability.

In satellite technology, cryogenic temperatures are essential for certain types of sensors and instruments, particularly those related to infrared (IR) and radiofrequency (RF) detection. Many telescopes, like the James Webb Space Telescope (JWST), rely on cryogenically cooled instruments to detect faint infrared signals from distant celestial bodies. Cooling these instruments reduces thermal noise and enhances sensitivity, enabling clearer and more precise observations. Without cryogenic cooling, IR detectors would pick up heat emitted by the instrument itself, overwhelming the signals from distant objects. Achieving such temperatures often requires advanced passive or active cooling systems, such as radiators or cryocoolers.

Space missions frequently employ cryogenic temperatures to store and transport fuels like liquid hydrogen and liquid oxygen, which are highly condensed at low temperatures but require robust containment solutions to prevent leakage or evaporation. The low temperatures of space make it possible to maintain these cryogenic fuels with minimal insulation; however, controlling the extreme temperature fluctuations of space remains challenging. Thermal management systems, including multi-layer insulation (MLI) and vacuum spaces, are essential in preserving fuel integrity for prolonged missions.

Cryogenic temperatures are indespensable in superconducting technologies, which hold promise for advanced computing in space in support of magnetic field measurement and IR detectors. Materials cooled to cryogenic temperatures can achieve superconductivity, where electrical resistance drops to nearly zero, allowing for efficient, high-performance circuits and sensors. Future Glenair interconnect technologies such as Constantan wire (under development) may someday play a role in such superconducting applications.

However, designing systems to operate at cryogenic temperatures involves overcoming significant engineering challenges. Material properties change significantly at such low temperatures, leading to brittleness in many metals and altering thermal and electrical conductivities. Future connector technologies for such cryogenic environments will need to address these challenges

Hermetic feedthroughs—used to isolate vacuum chambers from ambient gas—must be capable of withstanding both the cryogenic temperature of the vacuum chamber and the ambient temperature of free space.

An additional challenge in instrument-grade cryogenic applications is heat flow management as removing heat from a cryogenic system is difficult and requires considerable energy. In general, this is accomplished by

1) Making the coldest part of the system as small as possible.
2) Reducing thermal contact with warmer surroundings (for example with fewer and smaller wires).
3) Using thermally-insulating materials (special alloy wires).

The **James Webb Space Telescope** utilizes a cryogenic Application-Specific Integrated Circuit. This System Image, Digitizing, Enhancing, Controlling and Retrieving (or SIDECAR™) ASIC performs high-fidelity analog-to-digital signal conversion at cryogenic temperatures—and utilizes Glenair ThermaRex Cryo Nanominiature connectors.

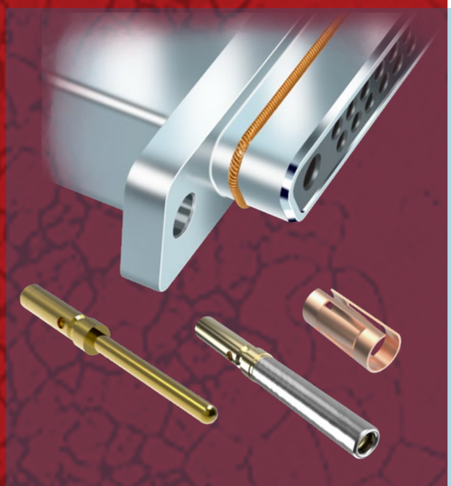
The telescope's lightweight mirrors are kept at cryogenic temperatures so the faint infrared light from distant galaxies is not lost in the mirror's infrared glow.

JWST's precision backplane carries over 2.5 tons of hardware and must remain steady and motionless at cryogenic temperatures to allow the precision instruments to operate accurately.

STRESS RELAXATION IN METALLIC MATERIALS AT ELEVATED TEMPERATURES

Stress relaxation in metals like beryllium copper is a crucial consideration in many engineering applications, especially when materials are subjected to elevated temperatures over extended periods. Stress relaxation occurs when a material under constant strain gradually loses its internal stress due to microstructural changes over time. This phenomenon can lead to a reduction in the material's mechanical performance, potentially compromising the integrity of the system if not adequately managed.

Beryllium copper, a copper alloy known for its high strength, corrosion resistance, and good conductivity, is frequently used in electrical and thermal applications where reliability is critical. This alloy, commonly found in connector ground springs, contact retention clips, and other components in electronics and aerospace systems, must often operate in environments where it is exposed to high temperatures. At elevated temperatures, the atoms in beryllium copper have higher mobility, which accelerates the process of stress relaxation. As a result, the alloy gradually loses its ability to maintain initial stress levels, which can lead to loosening in connectors or decreased tension in springs, adversely affecting the performance of the entire system.


EMI grounding springs, contact retention clips, and the contacts themselves use beryllium copper in their construction

The mechanism of stress relaxation in beryllium copper and other metals is rooted in the material's response to thermal energy. As temperature increases, dislocation motion and atomic diffusion become more active, causing atoms to shift into more stable positions that relieve internal stresses. This shift reduces the internal stress within the material even if the external strain remains constant. In beryllium copper, grain boundaries and phase precipitates play a significant role in this process, acting as sites where atomic rearrangements can occur, further contributing to stress relaxation.

Designers must account for the potential effects of stress relaxation when selecting beryllium copper or similar materials for high-temperature applications, as the material is particularly prone to this problem. Alternative materials such as stainless steel may be employed, as long as engineers are able to achieve a suitable balance between electrical conductivity, mechanical strength, and durability.

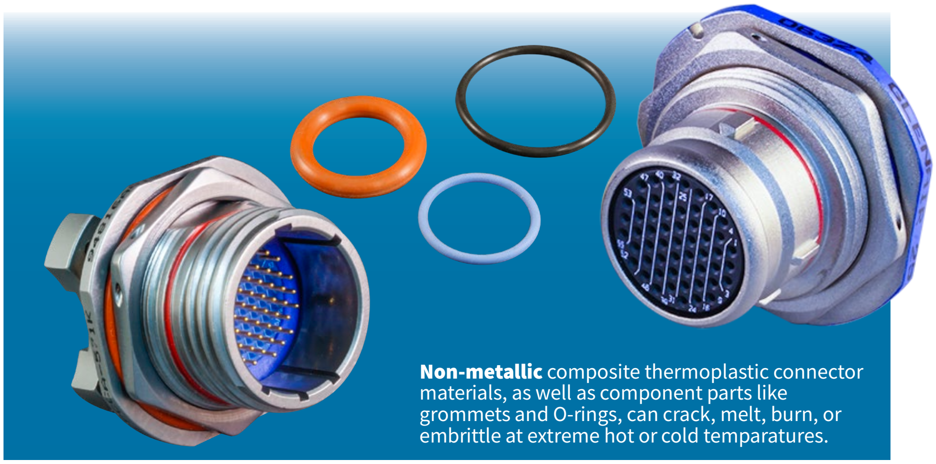
Understanding stress relaxation is particularly important in mission-critical applications where even small changes in mechanical and dimensional properties can lead to failure over time. In satellites, for instance, where high-temperature exposure is cyclic and unavoidable, tight dimensional tolerance in connectors and springs is essential to maintaining power and communication systems. Designers must carefully select and test alloys that can perform under such conditions, ensuring long-term operation.

Stamped and formed contact retention clips and grounding springs are also made of beryllium copper and would likewise experience stress relaxation if used at higher temperatures.

On the cold side of the scale, standard-environment materials will suffer from brittleness, cracking, loss of elasticity, and delamination of overmolding and cable jacketing from underlying structures if employed in continuous-use conditions lower than -65°C.

In addition, certain classes of plating and coating materials such as cadmium or zinc-nickel used extensively on mil-aero connectors, cannot be exposed to temperatures exceeding +175°C due to potential degradation or thermal oxidation of chromate conversion coating. For this reason, application engineers must pay careful attention to plating classes for derating of temperature tolerance below the standard defined range.

Thermoplastics are used extensively in standard mil-spec type interconnects. Polymeric thermoplastic connector shells and Thermoset insulators are perfectly suited for use within this standard temperature range, but will crack, melt, burn, or deform at higher temperatures, resulting in dielectric failure of the inserts. Thermal expansion and contraction becomes an issue with these materials and other non-metallic materials (such as adhesives and elastomers) at elevated temperatures. (See sidebar for more details on the use of composite thermoplastics and other non-metallic components in high temperature tolerant interconnect systems.)



Non-metallic composite thermoplastic connector materials, as well as component parts like grommets and O-rings, can crack, melt, burn, or embrittle at extreme hot or cold temparatures.

Rubber seal components (grommets, interface seals, and O-rings) can likewise lose elasticity, or crack and burn at higher service temperature than their continuous operating temperature rating. At cold temperatures, these rubber seals can suffer from embrittlement and cracking.

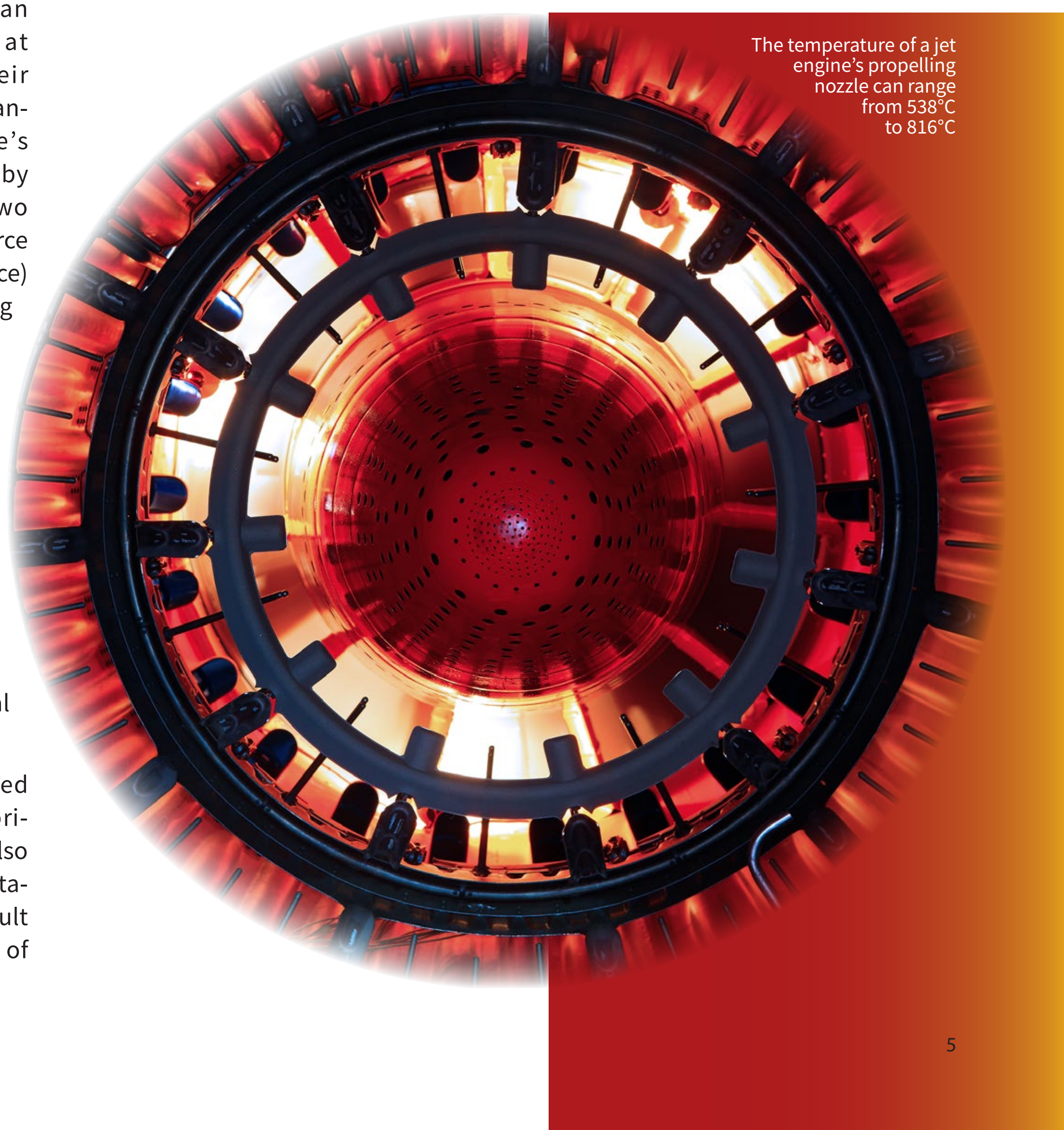
Insulator bonding adhesives experience reduction in adhesion strength (AKA lap shear strength) and can crack and ultimately detach at temperatures higher than their rating. Lap shear strength is a standard measure of an adhesive's bond strength. It is determined by the adhesive's ability to hold two surfaces together when a shear force (force parallel to the bonded surface) is applied. For insulator bonding adhesives, maintaining high lap shear strength is crucial because it ensures the insulation stays attached even under physical stress. However, at temperatures beyond the adhesive's specified rating, the adhesive's polymer structure begins to degrade. This degradation can take many forms: softening, loss of cohesive forces between polymer chains, or even chemical changes in the adhesive material.

Connector identification inks, red band paint, and wet or dry lubricants used on threaded surfaces also have operating temperature limitations that when exceeded will result in peeling and reduced legibility of marking.

For this reason, it is incumbent on application engineers to, again, pay special attention to actual operating temperature environments when specifying mil-standard metallic- and non-metallic connectors, and when necessary, recommend solutions with enhanced temperature resistance such as Glenair signature ThermaRex components.

For example, when continuous operating temperature ranges extend into the neighborhood of +260°C, Glenair recommends the use of upgraded materials and fabrication processes found in our ThermaRex ET (extended temperature) connector family, a new series currently in qualification testing.

Designed for use in SuperNine "better-than-QPL" MIL-DTL-38999 Series III packaging, ThermaRex ET satisfies the thermal compatibility demands for higher-temperature ranges up to +260°C.



The temperature of a jet engine's propelling nozzle can range from 538°C to 816°C

THERMAL EXPANSION AND CONTRACTION CHALLENGES IN COMPOSITE THERMOPLASTICS

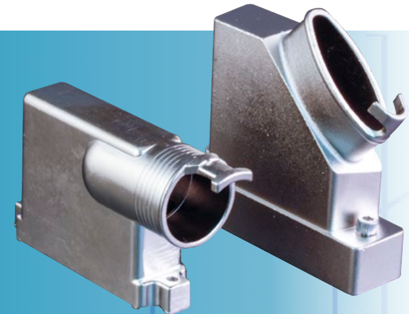
Thermal expansion and contraction present unique challenges in composite thermoplastics and other non-metallic materials, like adhesives and elastomers, especially under elevated temperatures. Unlike metals, which generally expand and contract in a predictable manner based on well-documented coefficients of thermal expansion, non-metallic materials can have complex, and sometimes nonlinear, responses to temperature changes. These responses can lead to dimensional instability, increased stress at joints and interfaces, and material degradation, all of which can significantly affect the integrity and performance of engineering systems.

In composite thermoplastics, thermal expansion is particularly complex due to the heterogeneous nature of these materials. Composites consist of different materials, such as fibers embedded in a polymer matrix, each with its own distinct expansion behavior. For instance, carbon fibers have a very low coefficient of thermal expansion, while the surrounding polymer matrix may expand considerably when heated. At elevated temperatures, this mismatch in thermal expansion can create internal stresses at the fiber-matrix interfaces, potentially leading to delamination, micro-cracking, or fiber pull-out. These issues not only compromise the mechanical properties of the composite but can also lead to performance degradation in structural and functional applications, such as aerospace components, where dimensional precision and strength are critical.

Adhesives and elastomers, often used alongside thermoplastics to bond or seal parts, also face challenges with thermal expansion and contraction. Adhesives, which are essential for bonding dissimilar materials, may exhibit differential expansion compared to the substrates they join. This discrepancy can lead to shear stresses at the bonded interface, resulting in adhesive failure, particularly in high-temperature environments where materials may soften and lose adhesive strength. Likewise, elastomers used for environmental sealing, may expand excessively under high temperatures, resulting in the loss of barrier integrity. Repeated thermal cycling in these materials can lead to stress accumulation and eventual material fatigue, further compromising performance.

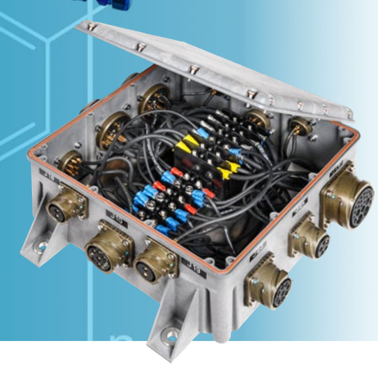
To address these issues, designers can select or modify composite thermoplastics, adhesives, and elastomers that are formulated to withstand elevated temperatures with minimal expansion. Special additives, fillers, and reinforcement fibers can be incorporated into the polymer matrix to reduce thermal expansion and improve dimensional stability. For example, using low-expansion fillers such as silica or carbon fibers can help balance the expansion coefficient in composites. In adhesives, certain formulations, such as those based on epoxy or silicone, are more resistant to temperature fluctuations and retain bonding strength better than standard adhesives.

Thermal expansion in non-metallic materials is particularly critical in industries like aerospace, automotive, and electronics, where even small dimensional changes can disrupt the alignment and functionality of high-precision components. Engineers working with these materials must account for thermal expansion and contraction in their designs, selecting materials with compatible expansion coefficients or incorporating flexible joints to accommodate thermal movement.









Glenair utilizes composite thermoplastic material for weight-saving connector accessories, fiber optic interconnect systems (including color-coded protective covers and protective conduit), 10K PSI pressure-rated underwater connectors, and rugged environmental junction boxes. For each application, engineers must consider the temperature exposure of the system.

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To survive in these extended-temperature application environments, **ThermaRex ET** utilizes various materials, including:

- Stainless steel connector shell and body components instead of aluminum.
- Stainless steel contact retention clips and EMI springs in place of beryllium copper stamped components.
- High-temperature Crown Ring contacts in place of standard 39029 split-tine sockets.
- Insulators fabricated from higher-temperature ceramics or thermoplastics such as PEEK.
- Specially formulated high-temperature silicone rubber O-rings and interfacial seals,
- Higher-temperature adhesives for all insert and assembly bonding operations.

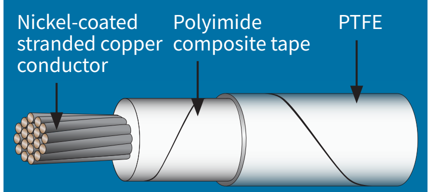
ThermaRex ET is supported by an ecosystem of complementary products. Most important of which is a high-temperature wire solution from the Glenair MIL-STAR family of hookup wires and cables that may be successfully paired with the extended-temperature ThermaRex interconnect. Glenair MIL-STAR nickel-coated copper PTFE / polyimide tape-wrapped wire is high temperature tolerant up to +260°C, as well as fire and chemical resistant and inherently low smoke.

Glenair signature ArmorLite braid is the EMI shielding solution of choice for +260°C applications. Supplied in 100% microfilament metal-clad stainless steel as well as hybrid configurations, ArmorLite is far lighter than conventional nickel-copper braid, offers outstanding EMI/RFI shielding and conductivity, high corrosion resistance, and superior flexibility and windowing resistance.

Polymer-core PFA conduit is an ideal wire protection solution for applications that require higher temperature protection up to +260°C compared to standard cable jacketing. Polymer-core PFA delivers outstanding lubricity and resistance to corrosion. The melt-extruded product offers outstanding cold flow and long-term sealing compared to other conduit material types.

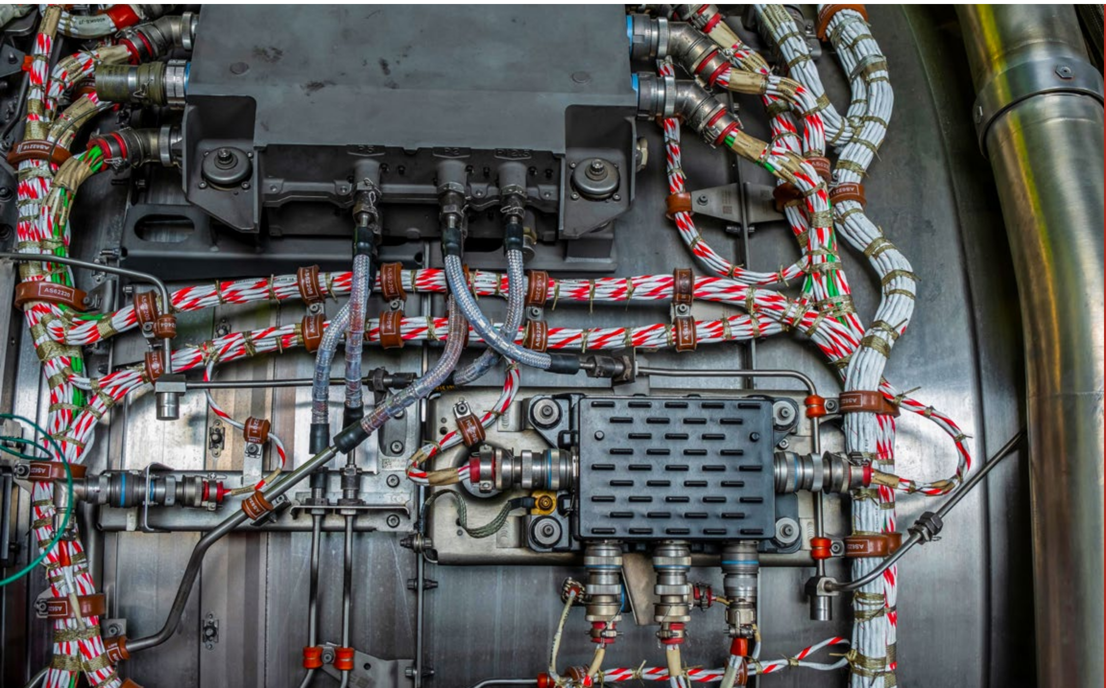
THERMAREX ET ECOSYSTEM COMPONENTS

MIL-STAR Wire: Nickel-coated copper, PTFE/Polyimide tape-wrapped. High-temp (260°C), fire and chemical-resistant, low smoke.



ArmorLite EMI shielding: micro-filament metal-clad stainless steel. Lightweight, corrosion-resistant, outstanding EMI/RFI shielding.

Series 74 Conduit: PFA material for high-temperature tolerance up to 260°C. A versatile wire protection solution compared to overmolded cable.



A Full Authority Digital Engine Control (FADEC) is a system consisting of a digital computer, called an “electronic engine controller” (EEC) or “engine control unit” (ECU), and related accessories that control an aircraft’s engine performance. These critical systems are located in the engine nacelle or mounted near the engine itself, and must be able to withstand extreme high and low temperatures. During flight, the temperature near the engine can exceed 200°C (392°F). At cruising altitude, temperatures can go as low as -65°C (-80°F). Electrical wire interconnect systems must be designed to withstand thermal cycling between these temperatures, as well as vibration and pressure extremes.

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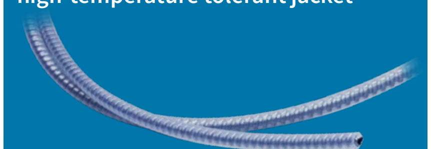
THERMAREX HT ECOSYSTEM COMPONENTS

MIL-STAR hookup wire with nickel-copper conductors and high-temperature thermoplastic insulation

MIL-STAR twisted-pair cable with ArmorLite CF lighweight braided shielding

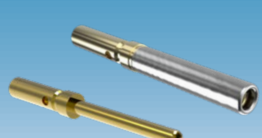
Polymer-core conduit—high-temperature tolerant PEEK

Metal-core conduit, 300°C continuous-service rated, with high-temperature tolerant jacket



ArmorLite CF lightweight micro-filament EMI braided shielding and PTFE glass tubular braid

Glenair signature Crown Ring high-temperature contacts prevent stress relaxation at elevated temperatures



ThermaRex HT (high-temperature) has been developed for applications that require continuous, reliable performance from -65°C to +300°C. This ThermaRex solution is available in a broader range of connector packaging including better-than-QPL MIL-DTL-38999 Series III SuperNine, micro-miniature Series 806 circular, and Series 79 high-performance rectangular. This technology can be adapted to other connector formats as required.

The heart of the ThermaRex HT design is its signature ceramic insulator, combined with high-temperature silicone O-rings and seals, and Glenair's high-temperature resistant Crown Ring socket contact which is supplied in sizes #23, #22, #20, #16, #12, and #8.

ThermaRex HT utilizes specially developed materials and processes for performance up to 300°C including:

- Machined connector bodies made of passivated stainless steel.
- Stamped EMI springs and contact retention clips made from high-temperature and stress-relaxation-resisting stainless steel
- Crown Ring socket contacts, made of high-temperature and stress-relaxation-resisting non-beryllium copper material.
- A special grade of high-temperature-resisting machined Ceramic insulator material which resists cracking and burning at continuous use up to 1000°C
- Connector seals made of signature Glenair high-temp silicone rubber
- And a Special grade of high operating temperature adhesives for insert bonding and assembly.

The ThermaRex HT high-temperature ceramic insert

All validation testing has been completed for ThermaRex HT including high-level random vibration at +300°C and 1000 hours temperature life cycling at +300°C. PC-tail configurations are available, as well as Hermetics up to +350°C.

Glenair has developed a special wire offering for use in ThermaRex HT applications: 961-047 high-temperature hookup wire with nickel-copper conductors and 300°C rated high-temperature thermoplastic insulation. Shielded twisted pair cables fabricated with 961-047 primary wires are ideally-suited for 300°C applications and are protected with Glenair ArmorLite CF lightweight microfilament shielding. The cables have been tested up to 2000 hours at 300°C. Qualification test reports are available.

ThermaRex HT signature series connectors

SuperNine® "better-than-QPL" D38999 high-temperature

Series 806 Mil-Aero high-temp micro-miniature

Series 79 Micro-Crimp high-temp rectangular

For wired conduit applications, Glenair offers 300°C-rated ThermaRex HT polymer-core lightweight conduit in a wide range of standard colors, backed by qualification testing demonstrating 300°C continuous service. ThermaRex conduit assemblies are available with high-temperature braided shielding and jacketing.

Glenair also offers a ThermaRex HT metal-core conduit capable of 300°C continuous service. 750-216 ThermaRex metal-core conduit is supplied with a high-temperature jacket and is available in .127" to 1/4 inch outer diameter sizes. Lightweight ArmorLite CF overbraiding enhances temperature tolerance from -80˚C to +400˚C. ArmorLite CF delivers 70% reduced weight vs. standard braid, superb electrical resistance and EMI shielding performance. Corrosion / harsh environmental resistance-tested to 1000 hours at 400°C (Test Report GT-20-766).

Glass-filled PTFE fire-resistant braided shielding is also suited for cable protection applications, such as for wiring adjacent to high-heat engine and ship galley locations. The material offers wire protection levels from -200°C to +525°C and is highly resistant to contaminants and toxic chemicals. This highly-flexible PTFE tubular braid presents a smooth surface finish that is resistant to snagging and breakage. The temperature range of this tubular shielding makes it ideally suited for ThermaRex HT-grade high-temperature applications.

The ThermaRex HT product family is ideally suited for interconnect applications in close proximity to aircraft engines such as FADEC controls. Other applications include hypersonic missiles, nuclear power, scientific research, space satellites, and launch vehicles.

CERAMIC MATERIALS FOR EXTREME-TEMPERATURE INTERCONNECTS

Ceramic materials play a critical role in ultra-high-temperature connectors and components used in aerospace and military defense applications. As these sectors demand materials that can withstand extreme temperatures, ceramics are often chosen for their unique properties, including excellent thermal stability, high melting points, and resistance to thermal shock, corrosion, and wear. These attributes make ceramics ideal for use in connectors and other components that must operate reliably in severe conditions where traditional metals and polymers would fail.

Ultra-high-temperature connectors are used in a variety of applications, including jet engines, missile systems, and other equipment exposed to extreme heat. Ceramics, such as alumina (Al_2O_3), silicon carbide (SiC), and zirconia (ZrO_2), provide a solution for components in these harsh environments. Alumina, for example, has a melting point above 2000°C and remains stable in oxidizing atmospheres, making it suitable for connectors that encounter high temperatures and oxidative conditions. Silicon carbide and zirconia, both high-strength and high-temperature ceramics, are also widely used in connectors and components exposed to friction, intense heat, or corrosive agents.

In aerospace applications, ceramic connectors must endure temperature fluctuations, high vibrations, and extreme altitudes without losing electrical or structural integrity. This is especially important for power and signal connectors in aircraft engines, where temperatures can exceed 1000°C. Ceramic materials ensure that these connectors remain stable, offering electrical insulation and mechanical strength even in the most intense thermal and mechanical stresses. Additionally, ceramics' low thermal expansion reduces thermal stress within the connectors, enhancing their lifespan and reliability over long missions or repeated thermal cycling.

Ceramics also excel in military defense applications, where components are subject to extreme environments and must perform under mission-critical conditions. Missiles, for example, rely on ceramic materials to maintain stable guidance systems and sensor functionality despite the high temperatures generated during launch and atmospheric re-entry. In defense systems that rely on radar, ceramics offer the advantage of being both heat-resistant and low in dielectric loss, which minimizes signal degradation while maintaining accurate communication and detection.

Despite these advantages, ceramics present some challenges in manufacturing and design. Ceramics are inherently brittle and can fracture under sudden mechanical loads, so engineers must carefully design components to avoid stress concentrations that could lead to failure. Advances in ceramic composites and improved processing techniques, such as the use of coatings and advanced joining methods, have made ceramics more adaptable to these demands by enhancing their toughness and reliability.

THE HOTTEST THINGS ON EARTH

Lava (Natural Hot)
Molten lava flows from Kīlauea Volcano, glowing with intense heat at over 1,200°C.

The Core of a Lightning Bolt (Natural Electric)
A lightning bolt tears through the sky, its core reaching 30,000°C, hotter than the surface of the Sun.

Solar Furnace (Man-Made Solar Concentration)
The Odeillo Solar Furnace focuses sunlight to produce temperatures of 3,500°C for scientific research.

Nuclear Fusion Reactors (Man-Made Physics)
Inside an experimental fusion reactor, plasma burns at 150 million degrees, mimicking the Sun's core.

Flames of a Blowtorch (Man-Made Tool)
An oxyacetylene torch flame blazes at 3,500°C, cutting through metal with ease.

Lut Desert, Iran (Desert Temperatures)
The Lut Desert scorches with a record-breaking ground temperature of 80.8°C, Earth's hottest surface.

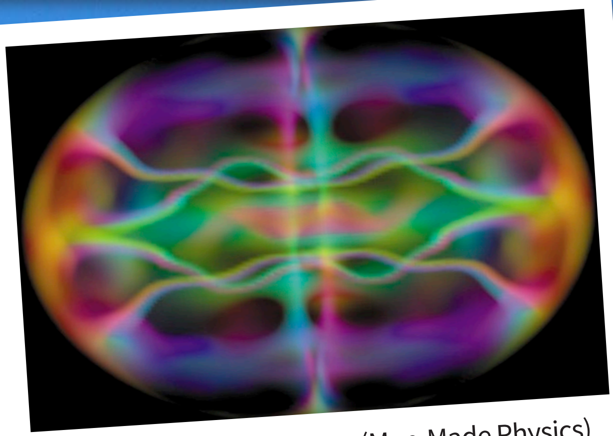
THE COLDEST THINGS ON EARTH

Vostok Station, Antarctica (Natural Weather)

Antarctica's Vostok Station holds the record for Earth's coldest temperature: −89.2°C.

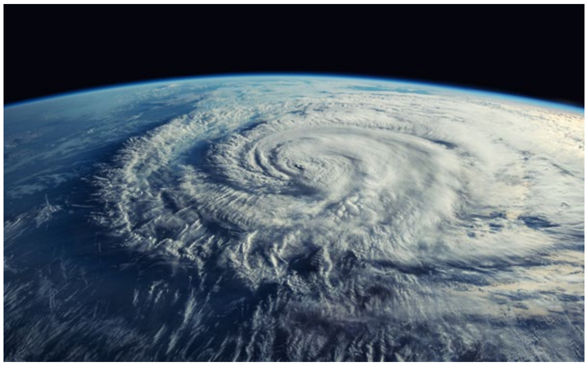
Cryogenic Liquid Helium (Man-Made Cooling)

Liquid helium, chilled to −269°C, keeps superconducting systems at extreme cold.



Bose-Einstein Condensate (Man-Made Physics)

Atoms in a Bose-Einstein condensate are chilled to billionths of a degree above absolute zero.



Cloud Tops in Tropical Storms (Natural Atmospheric)

The freezing upper clouds of a tropical storm hover at −83°C, shaping a dramatic skyscape.

Mount Everest Summit (Natural Extreme Altitude)

Winter temperatures at Everest's summit plunge to −60°C, an icy test of human endurance.

Deep Ocean Trenches (Subzero Waters)

In the abyssal depths of ocean trenches, water temperatures hover just above freezing at ~0°C, shrouded in eternal darkness.

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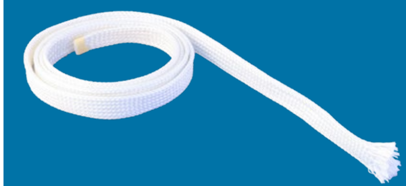
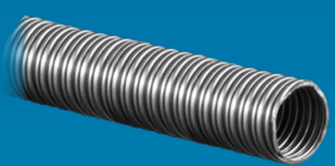
THERMAREX UHT ECOSYSTEM COMPONENTS

Mica-tape flexible ceramic-insulated ultra-high-temperature wire

Nextel 312 ceramic tubular braid: 1200°C continuous-use rated



Series 75 stainless-steel flexible wire protection conduit



Ultra-high-temperature tolerant Inconel backshell

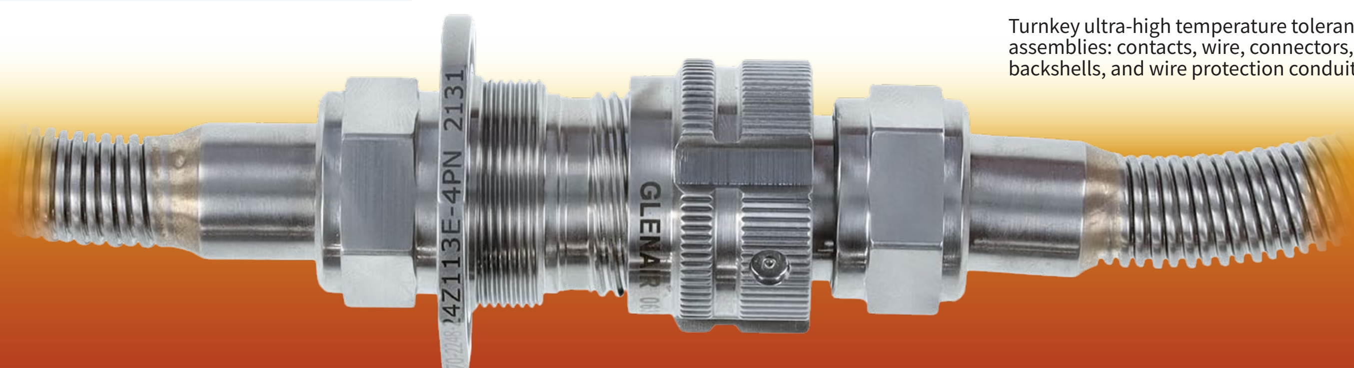
Our highest-temperature offering in the ThermaRex family is **ThermaRex UHT** or ultra-high-temperature, which is engineered to perform at operating temperatures up to 600°C. ThermaRex UHT is an ecosystem of technologies that includes ultra-high-temperature wire and tubular braided shielding. The ThermaRex UHT connector is precision-machined from Inconel, a nickel-chromium super alloy, and is supplied in the Glenair signature SuperNine package format. Inconel contacts are utilized as well, for ultra high-temperature performance.

Due to its extreme high temperature ratings, no rubber seals are used in ThermaRex UHT construction, and only special ceramic adhesives are employed. Inconel crimp-style contacts are utilized, in conjunction with a specially formatted high temperature-resisting ceramic insulator. The connector is vibration and shock resistant, EMI shielded, and has completed multiple rounds of development and design validation testing.

For 600°C ThermaRex UHT applications, Glenair supplies a wire solution with mica and ceramic insulation, with either 450°C rated copper or 600°C rated nickel conductors. This cable configuration is supplied in single hookup wires or as shielded twisted pair cables and is well-suited for applications that require a uniquely high-temperature wire solution. Unlike mineral insulated high-temperature wiring, ThermaRex UHT 961-087 cable is highly flexible, preferred for complex routing applications, and has been tested for survival at 880°C for one hour by a Glenair customer for a hypersonic missile application. See sidebar for more information on the science behind ceramic interconnect materials.

Nextel™ 312 tubular braid is composed of continuous ceramic fiber that offers strength and flexibility in constant high temperature environments. Its properties include low thermal conductivity and high thermal shock resistance, as well as low elongation, shrinkage, and moisture absorption making it ideal for applications that require an environmental flame barrier or thermal shield. It outperforms other high temperature textiles such as aramid and fiberglass in its chemical and abrasion resistance and is ideally suited for fire-resistant ThermaRex UHT applications. Nextel 312 also demonstrates favorable emissivity and high resistance to atomic oxygen, making it ideal for satellite applications.

Glenair Series 75 flexible metal-core conduit may be specified in passivated stainless steel for ultra-high-temperature resistance in the neighborhood of 350°C. Metal-core conduit of this type provides wire protection for non-jacketed cables and is typically factory-terminated and sealed with low-temperature brazing.



Turnkey ultra-high temperature tolerant assemblies: contacts, wire, connectors, backshells, and wire protection conduit.

NASA's SHIIVER tank, tested in the In-Space Propulsion Facility's vacuum chamber at Plum Brook Station, ensures that cryogenic fuels for deep space missions remain in liquid state despite the extreme temperatures of space.

The final offering in the ThermaRex product line is **ThermaRex Cryo**, which is low-temperature resistant to -200°C (73 Kelvin) and high-temperature resistant up to +200°C. Again, the connector is supplied in the SuperNine package format as well as the micro-miniature Series 806 circular.

The heart of the ThermaRex Cryo solution is its cold-temperature fracture-resisting insulator, and cryogenic temperature-resistant Duralectric K silicone grommet and interfacial seals. Electrical validation testing under D38999 shock and vibration levels, combined with simultaneous immersion in liquid nitrogen, has been completed with documented performance to -196°C. ThermaRex Cryo 806 qualification is complete for both environmental and hermetic connectors. Thermal shock from -196°C to +125°C, vibration in liquid nitrogen, and 300G mechanical shock in liquid nitrogen are all completed, demonstrating the robust performance of ThermaRex Cryo connectors.

Development of low thermal-transfer cryogenic conductors for space application harnesses is ongoing at Glenair. The goal is a crimp-contact capable wire, as solder process introduces unwanted corrosion. Glenair's space systems group in Salem is heading up this work.

Glenair has developed a family of flexible thermal straps for heat dissipation applications. The straps are used at thermal break points between ambient and cryogenic areas to moderate heat transfer that can impact performance of sensitive scientific equipment.

Micro-D and nanominiature interconnects, due to their low mass and low thermal conductivity coefficient, are ideally suited for use in cryogenic harnesses for space applications. Glenair QPL as well as signature micros and nanos have significant space flight heritage in both environmental and hermetic classes.

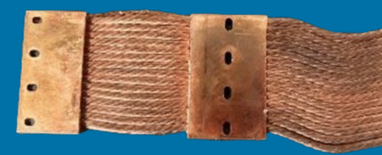
ThermaRex cryo products with hermetic insert sealing are ideally suited for both cryogenic propellant chamber applications as well as cryogenic instrument applications. Bulkhead feed-thru and weld-mount I/O hermetics have space flight heritage and TRL 9 status.

CRYOGENIC EQUIPMENT APPLICATIONS IN SPACE

The most common cryogenic interconnect applications are found in space. Cryogenic zones in space satellites are typically found in areas that house scientific sensors and instruments operating at low temperatures for improved sensitivity and reduced thermal noise. Equipment types include infrared sensors, microwave detectors, superconducting circuits, and deep space telescopes. In these applications, precise cryogenic cooling is essential for successful operation.

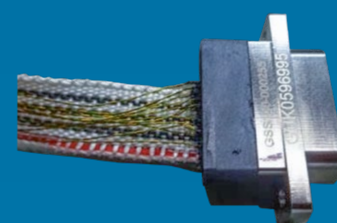
THERMAREX CRYO ECOSYSTEM COMPONENTS

Flexible thermal straps for heat dissipation



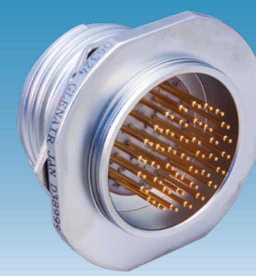
Low-temperature tolerant MIL-STAR nickel/copper-conductor wire

Low-mass / low-thermal-conductivity space-grade Micro-D cryogenic harness



Series 806 micro miniature circular. Environmental service-class rating down to -195°C

Hermetic-class
-195°C rating
<1X10^{-7} ccHe/sec hermetic seal

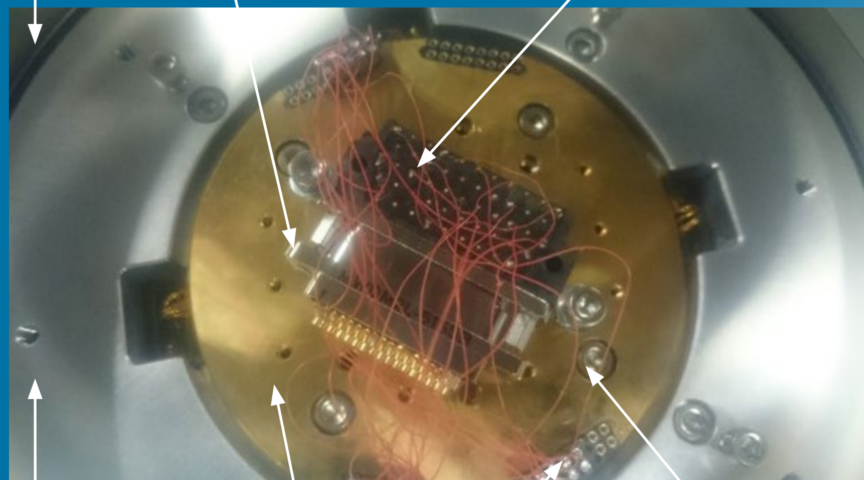


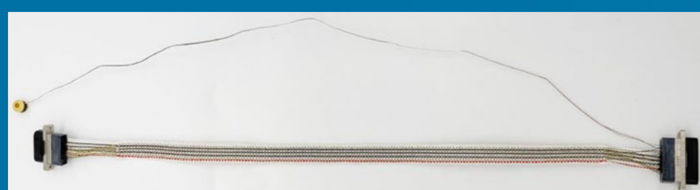
CRYOGENIC WIRE HARNESS CAPABILITIES FOR HEAT-SENSITIVE SATELLITE EQUIPMENT

GLENAIR SPACE-GRADE
CRYOGENICS

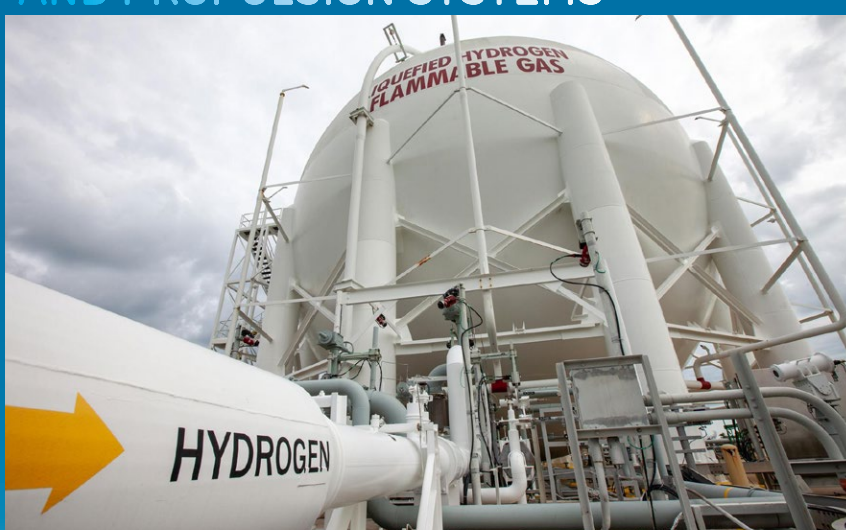
Glenair's space systems team in Salem, Germany, is carrying out extensive activity and investment in wire materials, termination processes, and equipment for space-grade cryogenic interconnect assembly applications. Development and qualification of exotic wire materials, and stripping, soldering, and crimping procedures, is underway with target temperatures of 100 K and 4 K. Assembly and verification processing is carried out in Class 8 and Class 7 cleanrooms and a Class 5 laminar flow chamber.

Cryogenic Connector Test @4 Kelvin—Glenair Salem, space systems test lab





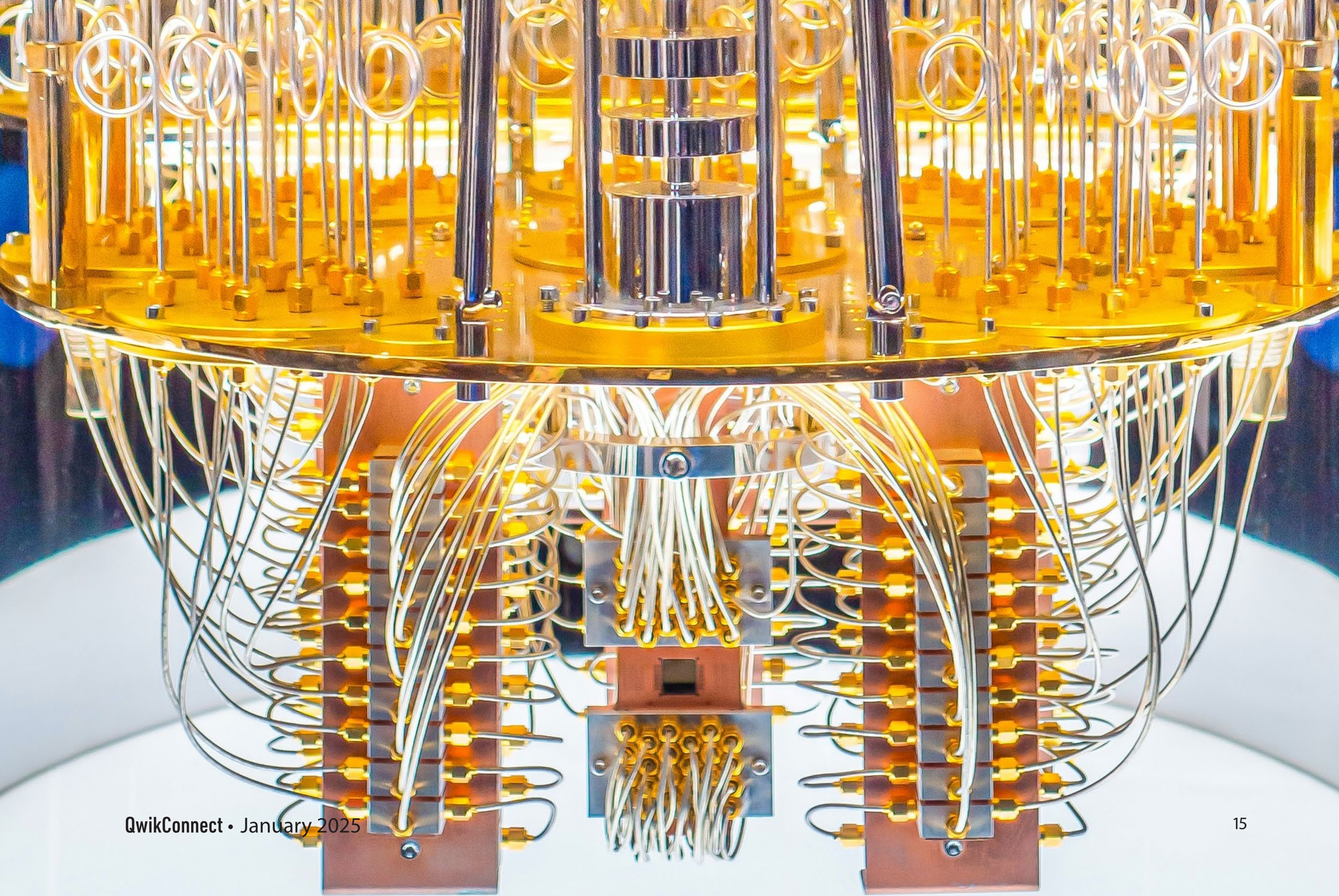
CRYOGENIC INTERCONNECT TECHNOLOGIES FOR FLUID STORAGE AND PROPULSION SYSTEMS



A liquid hydrogen storage tank at NASA's Kennedy Space Center's Launch Pad 39B, photographed during cryogenic system testing for the Artemis I mission. Liquid hydrogen propellant is lighter than liquid oxygen and will flow from the tank to the rocket using gaseous hydrogen to pressurize the sphere at the time of launch.

Photo: NASA

A second class of space-based applications centers around cryogenic fluid storage such as liquid hydrogen, oxygen, or methane for rocket launch propulsion systems. These propellants are stored at cryogenic temperatures to remain in liquid form. In applications of this type, it is essential for electrical wire interconnections to perform with minimal thermal transfer or conduction. For this reason, cryogenic fluid storage and propulsion system applications rely on ultra-low temperature tolerant interconnects such as ThermaRex Cryo Hermetics.



CRYOGENIC INTERCONNECT TECHNOLOGIES FOR QUANTUM COMPUTING APPLICATIONS

In the specialized field of quantum computing, electrical wire interconnects, particularly those handling RF signals, play a crucial role in linking quantum processors with classical control and readout systems. Such interconnect technologies must operate in demanding cryogenic environments, often below 1 Kelvin, to ensure quantum processors maintain coherence and perform optimally. Key considerations for these applications include:

Cryogenic Cooling Compatibility: Materials and components must maintain electrical and thermal performance under extreme cold while minimizing heat dissipation to preserve the cryogenic environment. This includes low-loss dielectrics and superconducting materials.

Low Magnetic Signature: Quantum systems are highly sensitive to magnetic fields, which can disrupt qubit states. Interconnects must be designed using non-magnetic or minimally magnetic materials to reduce interference.

Hermeticity: Hermetically sealed interconnects are essential to prevent moisture or contamination ingress, which can degrade computing performance at cryogenic temperatures.

High Signal Fidelity: RF interconnects must deliver high signal integrity with minimal attenuation and noise to ensure accurate control and readout of qubits.

Compact and Scalable Design: As quantum processors scale, interconnects must offer high-density solutions while maintaining the necessary performance requirements.

EXTREME-
TEMPERATURE
INTERCONNECT
ECOSYSTEMS

ThermaRex™

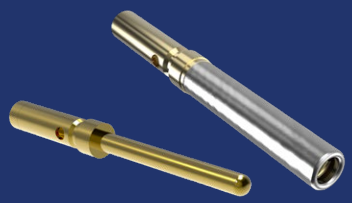
CRYO • HIGH TEMP • ULTRA HIGH-TEMP

Cryogenic and high-temperature tolerant connectors, cables, and conduit systems

ThermaRex UHT ultra high-temperature assembly: Series 806 connectors, high-temperature wire, high-temperature metal-core conduit.

Sensor devices in aerospace engine applications are increasingly exposed to higher temperature operating environments. Rugged sensors in FADEC equipment—an extreme high temperature environment—are also exposed to temperature extremes well beyond the capabilities of conventional interconnect devices. Glenair ThermaRex interconnect solutions are designed to survive and excel in high continuous operating temperature application environments up to 600°C.

HIGH-TEMPERATURE TOLERANT CROWN RING CONTACTS: ThermaRex™ HT SERIES



Glenair Signature Crown Ring contact series
provides reduced contact resistance, superior conductivity, and higher temperature-tolerance than conventional AS39029 contacts.

- Superior conductivity performance compared to beryllium copper contacts, across full temperature range
- Up to 60% lower contact resistance than AS39029 contacts (normalized, less wire)
- Contact bodies made from high-temperature and stress-relaxation-resisting non-beryllium copper material
- Stainless steel Crown Ring
    - Provides socket forces without stress relaxation at high temperatures
    - Moves socket spring function from socket body to ring, allowing use of high-conductivity copper
- Gold over nickel plating
    - Thicker plating than industry standards for reduced contact fretting and higher temperature endurance
    - Gold over nickel is "gold standard" for high-reliability aerospace contacts
- Crimp versions use standard industry tooling, including crimp die/locator and insertion/extraction tools (2AWG Crown Ring contacts require custom tooling)

HIGH-TEMPERATURE TOLERANT

ThermaRex Interconnect Solutions

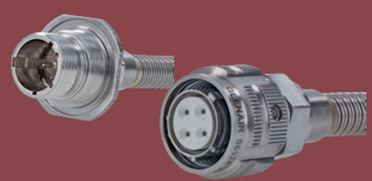
High-temperature, Ultra high-temperature, and Cryogenic

The ThermaRex product family includes wire, contacts, connectors, cables, and wire protection conduit systems organized into three temperature ranges: ThermaRex HT (high-temperature), ThermaRex UHT (ultra high-temperature), and ThermaRex Cryo.

+300°C ThermaRex HT Connector

- Service rating up to +300°C
- Vibration-resistant threaded coupling
- High-temperature ceramic insulators and silicone seals
- Durable stainless steel construction
- Available in Series 806, SuperNine®, or Series 79 rectangular
- Utilizes Glenair Crown Ring contacts

+600°C ThermaRex UHT Connector

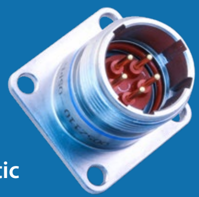


- +300°C to +600°C service range
- Vibration-resistant threaded coupling
- Specialized contacts, laser welds, and metal seals
- Utilizes ultra-high temperature flexible ceramic-insulated cable
- High-temperature tolerant ceramic insulators

-195°C ThermaRex Cryo Environmental and Hermetic Connectors

Environmental

- Environmental-class service rating down to -195°C
- Vibe and shock at D38999 level, immersed in LN2
- Cryogenic temperature-resistant Duralectric K grommet and interfacial seals
- Cold temperature-resistant thermoplastic dielectric insulator

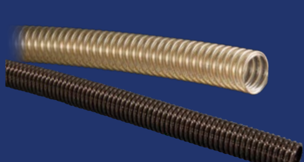


Hermetic

- Hermetic-class service rating -195°C to +200°C
- Series 806 micro-miniature high-density packaging
- Corrosion-resistant stainless steel shell construction
- Glass-to-metal hermetic seal leak rate <1 X 10^{-7} cc He / sec @ 1 ATM

Complementary ThermaRex Ecosystem Technologies

High- and low-temperature hookup wire and shielded twisted pair



High-temperature polymer-core wire protection conduit

Flexible stainless steel metal-core jacketed conduit

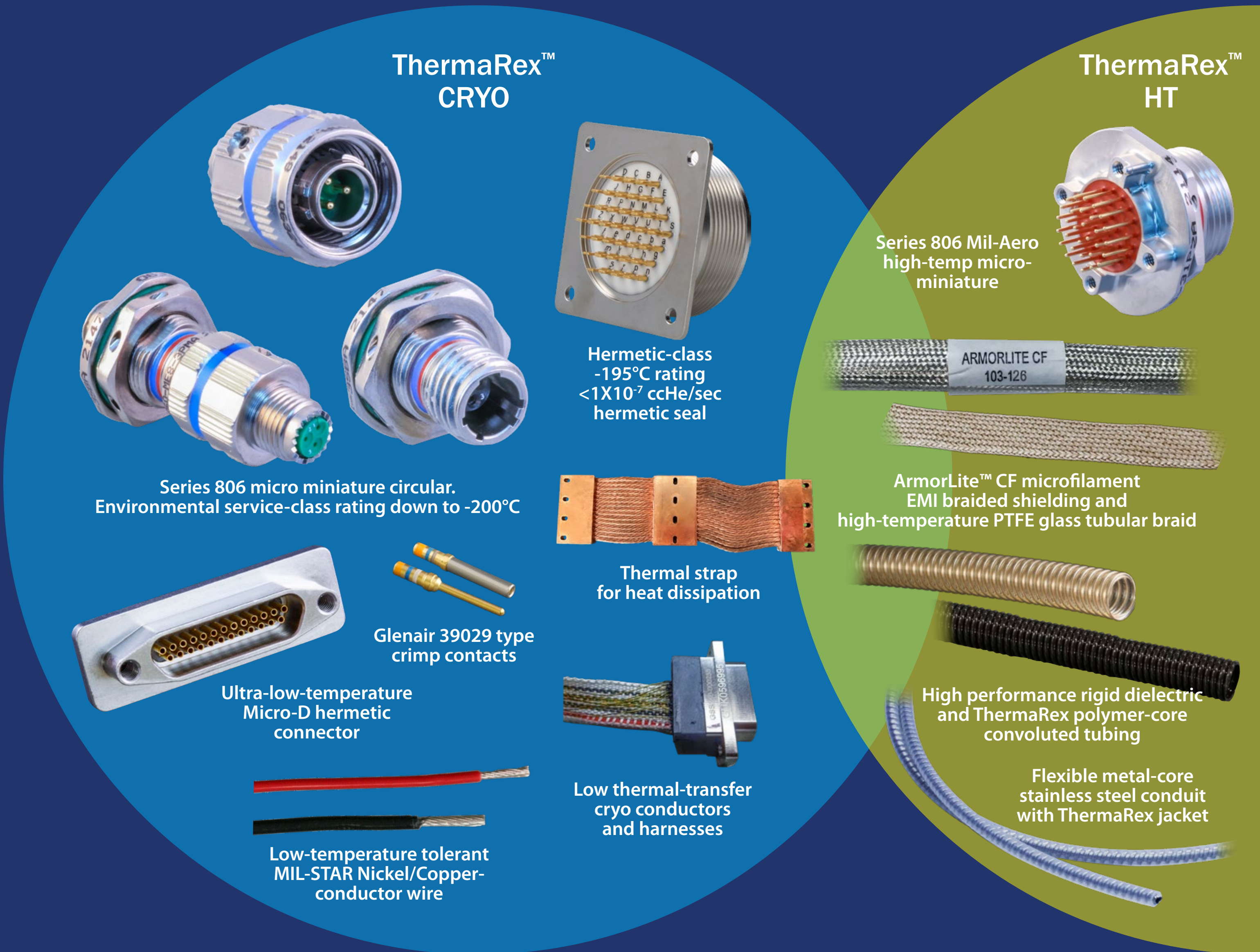
Three classes of HT and UHT flexible braided shielding

EXTREME-TEMPERATURE INTERCONNECT ECOSYSTEMS

ThermaRex™

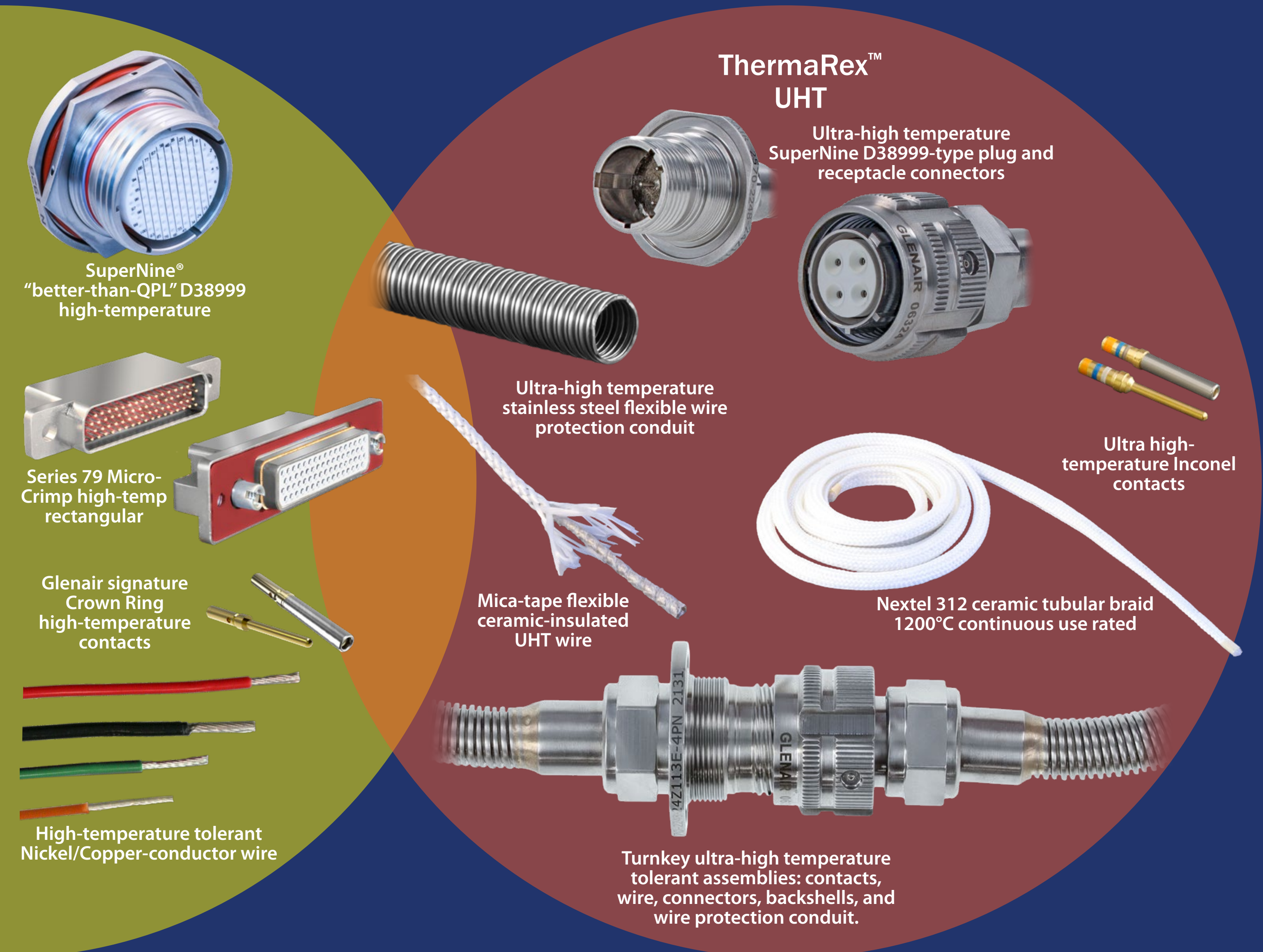
CRYO • HIGH TEMP • ULTRA HIGH-TEMP

Three distinct temperature-tolerant interconnect ecosystems for cryogenic, high-temperature, and ultra high-temperature applications



- Environmental-class service rating down to -195°C
- Hermetic -195°C
- High performance rigid dielectric insulators
- Duralectric™ K grommets and seals

- Environmental-class service rating up to +300°C
- Ceramic insulators
- Silicone O-rings and seals
- Stainless steel bodies



- **Environmental-class service rating up to +600°C**
- **Ceramic insulator**
- **Flexible ceramic-insulated cable**
- **Non-metallic seals**

Outlook

The Far Side of Complexity

I want to share a quote that absolutely reminds me of how the team at Glenair approaches its work. Oliver Wendell Holmes Jr. said, *"I would not give a fig for the simplicity on this side of complexity, but I would give my life for the simplicity on the other side of complexity."*

What Holmes meant—and what I see reflected every day at Glenair—is that simple answers at the onset of a challenge rarely if ever lead to success. I'm talking about quick fixes and surface-level solutions that might look appealing, but don't take into consideration the true complexity of an issue. Half of the wisdom here is simply accepting that efforts that don't address deeper issues will invariably leave the problem unresolved (or lead to new, unforeseen concerns). But the other half of the wisdom is realizing that when we truly tackle an issue in all its complexity, we can end up in a place—on the far side of the challenge—where our day-to-day life becomes amazingly simple.

Let's look at an example that is near and dear to all our hearts, our Same-Day Delivery Program. I think everyone would agree that our 30-year project of building out our massive raw material, component part, and finished-goods inventory position has been instrumental in establishing Glenair as a trusted, reliable partner in the high-reliability interconnect industry. Further, that our business lives have become—as a result of successfully tackling this complex project—incredibly simple. To accept that this is so, imagine how difficult competing in our industry would be without the ability to meet customer requirements as quickly and reliably as we do from stock.

Have you seen the Tom Hanks movie *Castaway*? It is a perfect analogy of Holmes' wisdom. Chuck Noland (Hanks) is a castaway trapped inside the calm waters of an island lagoon faced with the challenge of escaping through the massive, breaking waves of the outer reef. In his first attempt, he builds a crude raft and paddles straight at the waves. But they prove too strong for him. His raft is destroyed, and Noland is thrown back to shore, hurt and sickened. Do you then recall his laborious planning and building of a new raft? The careful marshalling of materials? The timing of his launch to coincide with the change in direction of the trade winds? And of course, the moment he overcomes the massive waves and looks back at the island from the calm waters beyond the reef?

Noland lived a simple, safe life in his lagoon. But he didn't give a fig for it. Instead, he was driven to understand the complexities of his dilemma, master them, and deliver himself from his island prison. The moment where he looks back at the island from the relative calm of the open sea is exactly where we want to be at Glenair: looking back at our most complex problems, enjoying calm, smooth sailing earned from a job well done.

Thanks to everyone on the team for getting us to, and keeping us on, the far side of complexity.

Chris Toomey

QwikConnect

GLENAIR • Volume 29 • Number 1

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QwikConnect is published quarterly by Glenair, Inc. and printed in the U.S.A.

A complete archive of past issues of QwikConnect is available on the Internet at www.glenair.com/qwikconnect

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