Designs of ultra-HPHT Electrical Component Packages for Downhole and Geothermal Wellbore Logging Tool Integrations

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Abstract
Conventional dielectric sealing materials (PEEK, glass and glass-ceramic) used for sealing electrical feedthroughs, connectors, interconnectors and bulkheads in electronic packages can provide reliable downhole wellbore long-term logging tool service up to 150°C or short-term logging service for ≥200°C, due primarily to low glass transition temperature of the used sealing materials. This paper will demonstrate that the maximum allowable operating pressure and temperature could be from 20KSI to 100KSI and from 200°C to 400°C with Borosilicate and Bismuth-Boron-Silica (XTS) sealing glasses. Borosilicate glass sealed Inconel-Kovar/Kovar electronic housing could maintain reliability up to the maximum pressures of ~35KSI at 200°C or 25KSI at 400°C. Similarly, a Bismuth-Boron-Silica XTS glass sealed stainless steel electronic package housing could have a maximum operating pressure of ~100KSI at ≤150°C or ~50KSI at 300°C temperature. It has been found that high glass transition temperatures of (440-560)°C for Borosilicate glass and (440±10)°C for Bismuth-Boron-Silicate (XTS) glass are key for making highly reliable ultra-HPHT electronic component packages. It is shown that the tetrahedral diamond-like microstructures of these sealing glasses are keys to ensure water-repelling properties to maintain sufficient electrical insulation resistance regardless of their use in water or moisture-rich wellbores. Moreover, compressive pin stress is found to be additional key for mitigate frequently observed glass seal cracks during logging tool field services.

Key words
Electrical component packages, downhole and geothermal wellbores, LWD/MWD tools, ultra-high-pressure and ultra-high-temperature.

I. Introduction
Electrical feedthroughs, interconnectors, connectors, and bulkheads are critical electrical components for packages or sub-assemblies used in most downhole and enhanced geothermal system (EGS) wellbore logging tools that may be deployed in a hostile environment with hydraulic pressure up to 40,000 PSI (40KSI) and elevated temperatures up to 400ºC [1-2]. Different from conventional downhole some geothermal wellbores are typically found to have far higher temperatures especially when located in harder sub-formations (i.e., igneous or metamorphic versus sedimentary for oil and gas). Current legacy packaging materials and logging tools reach operational limits at 150℃ for long-term use and 200-260℃ for short-term use, making these materials ineffective for broad use. For example, it is known that many geothermal wellbores have reported temperatures in excess of 200ºC with a few reported in excess of 371ºC. Although the hydraulic pressure may vary from 15KSI to 25KSI in most downhole and geothermal wellbores the dynamic or transient pressure variation could be as high as 40KSI with excited vibrational frequencies of 1-10 kHz.

High pressure could load significant mechanical stresses on an electronic package, which could in turn exceed the maximum allowed electrical and mechanical strengths of the sealing and packaging materials, thereby resulting in either or both catastrophic electrical or mechanical failure. Having both elevated pressure of >20KSI and temperatures of >200°C will carry with it significant challenges to glass-to-metal (GTM) hermetically sealed electronic packaging, when broken down are the basic integration of metals as the header, electrically conductive pins, and sealing glass created through a high-temperature firing process [3].

Designing feedthroughs, connectors, interconnectors, and bulkheads with mechanical compression is a basic requirement to ensuring that the package can be reliably operated under elevated temperature and pressure. However, such a package may mechanically survive high temperature and pressure conditions but it could electrically fail as a result of temperature-induced loss of the electrical insulation resistance. Additionally, an electronic package may withstand elevated temperatures but it could mechanically fail by high pressure-induced loss of hermeticity. Furthermore, the hydrophilicity of the sealing material may also cause electrical failures as a result of the loss of electrical insulation resistance due to moisture ingress especially found in moisture-rich downhole or geothermal wellbores. In current designs; electrical feedthroughs, connectors, interconnects, and bulkheads operating at a typical maximum temperature of ≤177ºC and a typical maximum pressure of <20KSI, have been defined as high-pressure and high-temperature (HPHT) electrical component packages [2]. The demands don't stop there. In a geothermal or EGS wellbore these packages are also required to be operable in salt water, CO_2 or H_2S, and corrosive fluid. Withstanding high pressures and temperatures is a challenge - one that becomes even more complex when brine, sour gases, and corrosive fluids are added to the challenge. Given that it is of great technical interest in how an electronic component package can be designed to reliably withstand ultra or extra high-pressure and high-temperature downhole and geothermal wellbores for long-term operation.

Inconel alloys, hastelloy, and stainless steels are available as header or/and shell materials that can chemically resist corrosive fluids but also mechanically withstand 400°C/40KSI harsh conditions as a result of their excellent mechanical and chemical strength(s). For example, Inconel alloys (625, 718, and X750) exhibit excellent mechanical and anti-corrosion performance, while 304L/316L/317L stainless steels can be used as a result of their excellent resistance to reducing and oxidizing acids or acidic chloride, or to sour gas-rich corrosive fluids. Inside the header or/and shell assembly, Ni, Au or Ni/Au electroless or electrolyte plated Inconel X750, Alloy 52, BeCu, and Kovar materials are often used as the electrically conductive pins. For example, a BeCu pin of 1.6 mm diameter may be an option for a high-power signal transmission that requires 30 amps current capacity. However, an Alloy 52 pin of 0.76mm diameter may provide ~1.2 amps current capacity. To effectively bond the metal header/shell and the electrically conductive pins while affording electrical insulation, a dielectric sealing material has to be used to build a GTM hermetically sealed electronic package.

The conventional feedthrough, connector, interconnector, and bulkhead sealing process is to bond the header and pin(s) together in an assembly with a dielectric sealing material, such as PEEK/Teflon polymer, glass, and glass-ceramics. Since polymer seals alone cannot provide for truly hermetic packaging, and conventional sealing glass is more or less hydrophilic, it has become common practice to seal an electrical component first with glass material, via a high-temperature GTM firing process which can provide for sufficient hermeticity, then to additionally protect the components front face with the addition of a PEEK/Teflon polymer provided via a polymer injection molding process that is intended to limit the ingress of water and or wellbore fluids into the sealing glass material. However, it should also be known that PEEK is a polymer material that can absorb 0.1 wt.% water over 24 hours; and that its glass transition temperature of ~143°C will limit the maximum operation temperature of less than 150°C.

In this paper a previously developed thermo-mechanical stress model has been used to explore the feasibility for making ultra-HPHT (HPuHT, uHPHT and U-HPHT) electronic component packages that may be capable of withstanding 200-400°C temperature and 30-100KSI pressure in a downhole or geothermal wellbore [4-5]. More specifically, we've shown that borosilicate glass has been used for making high-pressure/ultra-high-temperature (HPuHT) electronic component package because of its excellent mechanical, and chemical properties, as well as its high glass transition temperature of 440-560°C. Additionally, we'll show that the Bismuth-Boron-Silica, or XTS, glass has been found to be a superior sealing material candidate that exhibits not only high water repelling capability, but also ultra-high pressure resistance (uHP) and ultra-high temperature resistance (uHT). This new XTS material exhibits breakthrough performance in creating the next generation of electronic packaging for use in harsh applications that exhibit high levels of performance in combinations of both ultra-high-pressure and ultra-high-temperature (U-HPHT) environments.

II. Results and discussion

A. Modeling of simplified electrical component package

An electrical feedthrough, interconnector, connector or bulkhead penetration component for electronic packaging basically consists of three sub-components: the header, seal, and pin. Each sub-component has different geometrical sizes, form factors and material properties. Most specifically, there will exist different thermal expansion coefficients among these three sub-components, which will lead to different stress points at the material interfaces. For example, the seal will be in compression status if the coefficient of thermal expansion (CTE) of the metal header is much higher than that of the dielectric sealing material. However, the stress of the pin sub- component may vary from compression to tension, determined by CTEs of both sealing and pin materials.

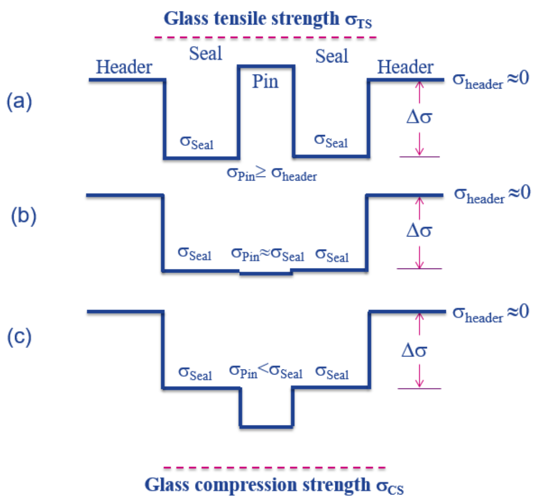

Figure 1 Mechanical stress status of a simplified electrical component assembly model and corresponding thermo-mechanical stress amplitudes (Δσ), determined by CTE differences among header, sealing glass and pin materials.

Figure 1 describes the mechanical stress status in each sub-component (σ_{header}, σ_{seal}, σ_{pin}), where $\Delta\sigma=\sigma_{header}-\sigma_{seal}$. Stress being defined as thermo-mechanical stress well amplitude that will determine maximum pressure limit of an electrical component package operation. Figure 1(a) reflects an electrical component having a compression seal for enabling high pressure operation, but $\sigma_{Pin}\geq\sigma_{header}$ indicates the CTE of the pin material is higher than those of the sealing glass and header materials. Figure 1(b) describes a compressive electrical component for withstanding high pressure with similar CTEs between sealing glass and pin material that only induces very little interfacial stress. While Fig.1(c) illustrates an electrical component has high compression and high compressive pin stress, which may be desirable for mitigating potential sealing glass cracks, especially when the package is deployed at a vibrational Oil/Gas exploration field.

When the pin stress is tensile but it has to be lower than maximum tensile strength (σ_{TS}) of the sealing material because high-CTE pin may crack the sealing glass under rapidly thermal shock events. In an extreme case of pin stress greater than maximum sealing glass tensile strength, i.e., $\sigma_{Pin}\geq\sigma_{TS}$, the seal glass may be cracked immediately after GTM fabrication process. To the contrary, the extremely high compressive pin stress in Fig.1(c) may also cause sealing glass interior cracks especially around defects, dislocations, and voids if the pin stress is close to maximum sealing glass compression strength, namely, $\sigma_{Pin}\approx\sigma_{CS}$. The propagation of the cracks along the pin surface may lead to loss of the hermeticity. For making a reliable package it is desirable to have a safety factor of ≥2.0, defined by $\sigma_{TS}/\sigma_{Pin}\geq2.0$ and $\sigma_{CS}/\sigma_{Seal}\geq2.0$, which are determined by CTEs of all the sub-components and design geometries in pin diameter, glass sealing diameter, and pin sealing length.

B. HPuHT electrical component package

A high-pressure (>20KSI) and ultra-high-temperature (>200°C) electrical component package is desirable for operating in any downhole and geothermal EGS wellbores that have a bottom hole temperature much higher than 200°C. Obviously, the glass material is a critical element that should have high mechanical and chemical strength as well as high glass transition temperatures of >200°C. Boron-Silica based Borosilicate glass is a type of glass with the main glass-forming constituents of silicon dioxide and boron oxide with a ~4ppm/°C coefficient of thermal expansion that makes it more resistant to thermal shock events. This sealing material has a glass transition temperature ranging from 440 to 560°C, depending upon the percentage (75-85%) of silicon dioxide constituent in the glass. In addition, it has a maximum tensile strength of ~80 MPa and maximum compression strength of ~870 MPa. More importantly, this sealing glass can be engineered to turn its hydrophilic property to water-repelling property by turning its amorphous structures into tetrahedral nano-crystallites dominant microstructures, obtained by combining a high firing temperature (~1100°C) and cooling rate (<10°C/min) GTM sealing process. Although Kovar is broadly used in glass sealing applications in the electronics industry, the 53% iron constituents in Ni-Co-Fe Kovar alloys limit their use for as HPHT electrical components or packages due mainly to the lack of corrosion resistance.

To enable Borosilicate glass sealed Kovar assemblies to be resistant to corrosive fluids and downhole harsh environments, the header should be protected by an anti-corrosion metal. Explosion welded binary metal materials are pretty matured technology for bond dissimilar metals together by explosion welding process [7]. With explosion welded binary-metal materials of Inconel-Kovar or stainless steel-Kovar an electrical component package could have Inconel or a stainless steel as outer shell and an explosively bonded Kovar as inner shell. In this process, an Inconel alloy (625, 718, X750 etc.) or stainless steel (304L, 316L, 317L, 430 etc.) based outer shells could provide the high resistance to corrosion and HPHT harsh conditions while the Kovar based inner shell is still used for the Borosilicate glass sealing with Kovar pins.

Figure 2(a) shows the stress profiles of a simplified assembly of a Borosilicate glass sealed Inconel-Kovar explosion welded material built using a Kovar pin(s) in a temperature range from -100°C to 400°C. The design considers pin and seal diameters of 0.46mm and 1.42mm respectively, with a minimum sealing length of 10.2mm. The temperature-dependent seal stress amplitude is about -170MPa at -100°C and still maintains desirable compression of about -60MPa even at 400°C. Similarly, when the temperature varies from

-100°C to 400°C the pin stress amplitude has only changed from -30MPa to -10MPa, where the negative or compressive pin stress amplitude basically enables high thermal shock resistance that could mitigate potential glass cracks.

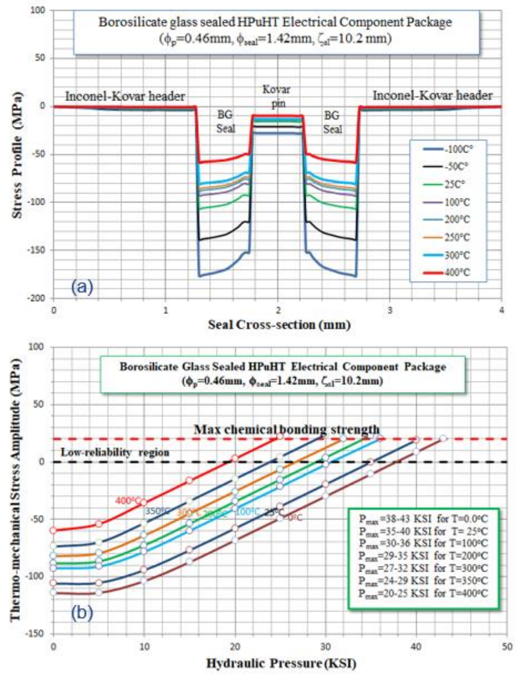

Figure 2 (a) temperature dependent seal compression for Borosilicate glass sealed HPuHT electrical component package, and (b) thermo-mechanical stress amplitude determined maximum allowed pressure ranges.

Figure 2(b) further illustrates that a Borosilicate glass sealed Inconel-Kovar header/Kovar pin component may be capable of operating up to 400°C, and the maximum pressure may be operable up to 40KSI. Especially, this electrical component package may have maximum operating pressure of 35KSI at 200°C. However, this package will be not reliable when the seal stress amplitude is higher than the maximum chemical bonding strength, as labeled by dashed red line. In addition, this package is operated under low reliability region if its compression or thermo-mechanical stress amplitude is between 0 and 20MPa. By its high-pressure and ultra-high-temperature (HPuHT) capabilities this Borosilicate glass sealed electrical package could be a candidate for signal, data, and electrical power transmission from most hostile downhole or/and geothermal/EGS wellbores.

C. uHPHT and U-HPHT electrical component packages

In an extra high-pressure (≤100KSI) and high-temperature (>200°C) geothermal wellbore, there are no conventional electronic component packages available due to the lack of proper sealing glass that exhibit both high mechanical strengths and a high glass transition temperature of >200°C. Bismuth-Boron-Silica, or XTS based sealing glass, is a type of nano-crystalline glass-ceramic with a (6.5±0.5) ppm/°C coefficient of thermal expansion that allows for more metals to become header candidate materials [3-4, 6]. Additionally, its water-repelling properties make it resistant to moisture-induced electrical insulation loss. This sealing glass material has a glass transition temperature of 440±10 ºC, depending upon the ratio of silicon dioxide over bismuth oxide constituents. The maximum tensile and compression strengths of this sealing glass are ~70 MPa and ~700 MPa, respectively. Similarly, it also exhibits diamond-like tetrahedral nano-crystalline microstructures.

Figure 3(a) shows the thermo-mechanical stress profiles across a seal cross-section from an assembly made from an XTS glass sealed 304L stainless steel header, built to resist chemical corrosion in a downhole corrosive fluid. For low-power (<10 amps) signal transmission, many pin materials could be used, such as Inconel X750, Alloy 52, Ni, CrCu, Cu, BeCu, and Kovar with different AWG gauge sizes. However, Alloy 52 has a CTE of ~10 ppm/°C that could effectively reduce stress at pin/sealing glass interface. The observed seal compression is about -520MPa at -50°C but it is reduced to about -150MPa at 300°C. Meanwhile, the stress difference between pin and seal has only changed from 40MPa at -50°C to 10MPa at 300°C, which is due mainly to the CTE of Alloy 52 being ~10 ppm/°C pin. Noticeably, this high compression package/component is more likely to provide mechanical resistance against glass cracks induced

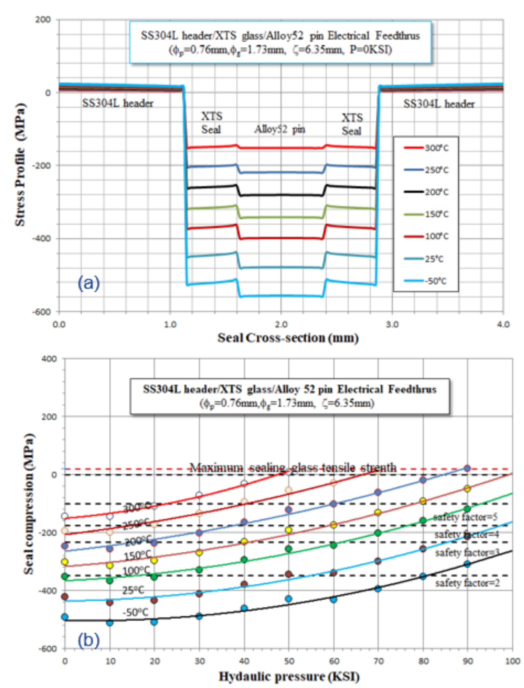

Figure 3 Temperature dependent maximum allowed pressures from a XTS glass sealed 304L stainless steel and Alloy 52 pin integrated electrical component package.

hermeticity loss, especially during deployments in harsh logging tool field service environments.

Figure 3(b) shows maximum allowed pressures at different operating temperatures using the Bismuth-Boron-Silica (XTS) glass sealing material in a 304L stainless steel header with an Alloy 52 pin, which may be capable of operating up to 50 KSI at 300°C or up to 100KSI at ≤150°C. Limited by the maximum Alloy 52 pin current capacity of 1.2 amps, this designed electrical component package could be used for low-power signal and data transmissions in ultra-high-pressure environments up to 100KSI (uHPHT) downhole or ultra-high-pressure and ultra-high-temperature (U-HPHT) downhole and geothermal wellbores.

Another example of a high-power corrosion resistant electrical component/package is based on using 316L stainless steel metal as the header material and a gold plated BeCu pin, which is shown to be resistant to both reducing and oxidizing acids due to its Mo content. A feedthrough with this combination can be used in brine and sour gas electronic component design that have electrical pin current capacity of ~30 amps with a 14 AWG BeCu pin (1.57mm ϕ_{pin}). Figure 4 shows thermo-mechanical stress amplitudes and maximum pressures based on the Bismuth-Boron-Silica

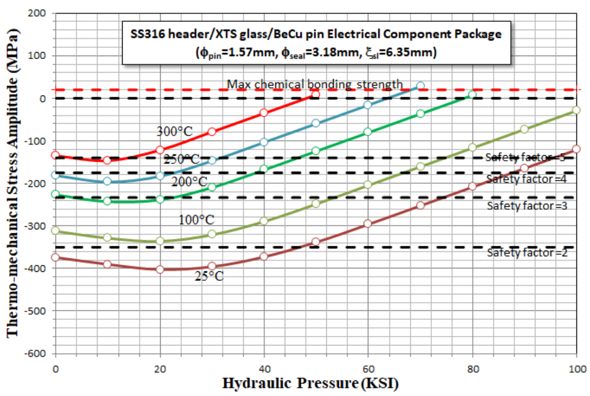

Figure 4 Maximum allowed pressures at different temperatures from a XTS glass sealed non-magnetic and anti-corrosion 316L stainless steel and gold plated BeCu pin assembly.

or XTS glass sealed 316L stainless steel header with a BeCu pin assembly designed for high-power (>10 amps) signal transmission, where the downhole temperature varies from 25°C to 300°C. The maximum allowed pressures of this package could vary from 80KSI at 200°C to 50KSI at 300°C. It should be noted that this electrical component package may be capable of operating up to 100KSI at ≤120°C temperatures. Based on its 440±10°C glass transition temperature and ~5,000 MΩ electrical insulation resistance at 300°C [3-4], it is expected that the maximum allowed operating pressures could be likely from 50KSI to 100KSI for signal, data, and high electrical power transmission.

III. Conclusion

Two interesting sealing glasses, Borosilicate and Bismuth-Boron-Silica, have been proposed to make ultra-HPHT electrical component packages for LWD/MWD logging tool integrations. The high mechanical and chemical strengths, water-repelling properties, and high glass transition temperatures enable the sealed packages to be reliably operated in either extra-high-pressure environments up to 100KSI or ultra-high-temperature ranging from 200°C to 400°C. Especially, the water-repelling properties of these insulating materials could provide an excellent advantage over existing hydrophilic sealing glass for the water or moisture-rich wellbore logging and exploration.

The addition of explosively bonded/welded metals to these packages, such as Inconel-Kovar and stainless steel-Kovar, are shown to be able to operate in corrosive ultra-HPHT wellbores. This paper has disclosed that the maximum allowable operating temperature from Borosilicate glass sealed Inconel-Kovar/Kovar package could be operated up to 400ºC. Similarly, the Bismuth-Boron-Silica (XTS) glass sealed stainless steel based packages could have a maximum operating pressure up to 100KSI even at 120-150°C. Specifically, the high glass transition temperatures of two sealing glasses are the key for making ultra-HPHT (HPuHT, uHPHT, U-HPHT) electronic component packaging for LWD/MWD logging tool integrations.

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