ENHANCED ELECTRICAL PENETRATION COMPONENTS MEET THE HIGH SAFETY STANDARDS REQUIRED FOR CHINA'S HTR-PM SHIDAOWAN AND GENERATION MPOWER SMALL MODULAR REACTORS

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ABSTRACT

Enhanced glass-to-metal feedthroughs will be used to carry key instrumentation and control (I&C) signals in China's high-temperature, gas-cooled pebble-bed modular reactor (HTR-PM) at Shidaowan, and in Small Modular Reactor (SMR) prototyping.

Chinergy Co., Ltd and Jiamusi Electric Machine Co., Ltd will use the feedthroughs, also called electrical penetration assemblies (EPAs), at the Shidaowan twin-reactor high temperature reactor (HTR). These feedthroughs are manufactured using specialized processes that make them far more robust than counterparts made with organic or ceramic materials.

Improved EPAs manufactured by SCHOTT are the only feedthrough solution that can be used in the primary loop of an HTR because organic seals cannot withstand the high temperatures and pressures of this environment.

Glass-to-metal seals (GTMS) are made using inorganic, non-aging materials which enable a virtually unlimited lifespan in high-temperature, high-radiation and high-pressure applications. This I&C technology package is being enhanced by the development and testing of new mineral-insulated (MI) cable connectors and EPAs made of crystallized glass-ceramic combined with superalloys.

The EPAs have a maintenance-free lifespan of over 60 years, preventing any outage time related to these components and subsequently reducing costs associated with shutdowns. They are far more robust than organic seals and provide increased safety at a lower lifetime cost. Resistance against high pressure and high temperature are especially ideal qualities that make EPAs a valuable choice for environments with high standards for fire protection, such as nuclear plants, subsea oil drilling, or any other underwater application.

Due to their significant offering of safety-relevant qualities, the EPAs have also been chosen by BWXT for implementation in its mPower SMR. Small modular reactor requirements are complex and very challenging but are met by the new EPA components, which will help form a strong I&C safety chain. Unlike ordinary compression glass-to-metal seals, GTMS with cristallized glass-ceramic have the ability to withstand temperatures of over 350° C / 662° F and operating pressures of 3500bar. Furthermore, their lifetime is qualified for up to 60 years, including pressure and radiation requirements in accordance with the latest IEC/IEEE standards.

Higher-specification EPAs and MI cable connectors have been designed into severe accident I&C instruments, including advanced hydrogen and oxygen sensors that exceed the challenging requirements of both HTR and SMR applications.

Key Words: reactor penetrations; HTRs; higher safety standards, severe accident I&C

1. INTRODUCTION

An EPA, or feedthrough, consists of insulated electric conductors, conductor seals, module seals, and aperture seals that allow integrated through-wall passage of electric conductors in the nuclear containment and primary loop, all while maintaining pressure integrity. EPAs are uniquely designed to exceed the performance attributes of the containment and primary loop in order to comply with international safety standards.

EPAs are a key element of nuclear safety and typically integrated into class 1E electrical systems. This setup can include terminal or junction boxes, terminal blocks, connectors, cable supports, and splices to ensure flawless incorporation of the power, control and I&C systems.

Matched glass-to-metal seals

Historically, components known as **matched glass-to-metal seals** were the first step of evolution in this field of application. Manufacturers accomplished significant temperature operation ranges as well as flawless function after tens of thousands of thermal cycles by combining glass and metal with similar coefficients of thermal expansion (CTE). This ensured the glass-to-metal feedthrough contained virtually no stress at room temperature or at the working temperature of the final product.

A notable advantage of this type of seal is the possibility to make more conductors fit into a given housing area. Thinner material cross sections can make the parts lighter in weight.

1.2 Compression glass-to-metal seals

To further improve GTMS ability to withstand corrosion or high pressure, or if conductor strength is of primary importance, a GTMS with matched CTE is not the perfect approach. For such fields of application, a **compression glass-to-metal seal** is the better-suited solution.

In such seals, stress inside the glass is avoided – a specific type of stress is purposely designed into the part, varying by application area. Glasses have a compressive strength that is many times higher than its tensile strength. This characteristic is utilized to improve the strength of the seal by choosing metals for the housing with a much higher CTE than that of the glass and the interior wire (see chapter 3.1).

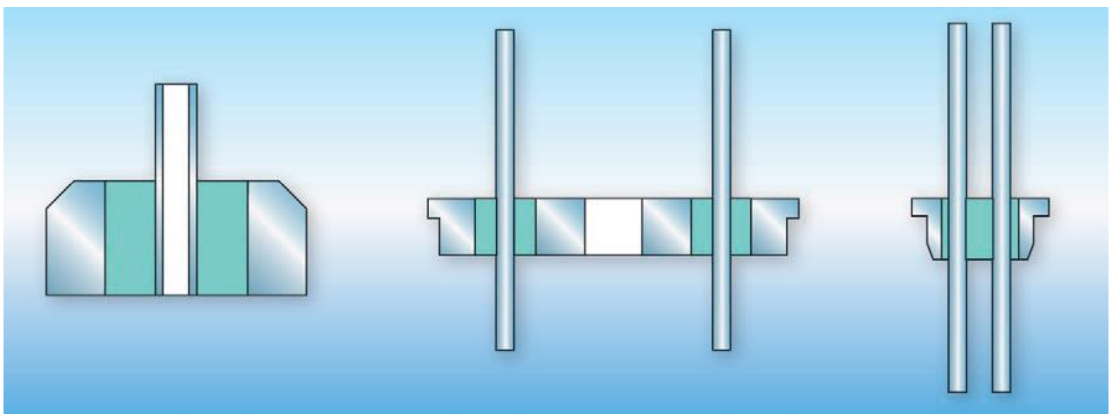

Figure 1. Typical designs of Compression glass-to-metal seals.

1.3 Crystallized glass-ceramic metal seals

With rising guidelines and demands for material performance, the specialty glass core is now being substituted with crystallized glass-ceramic. The glass-ceramic is molten at 950°C / 1742°F and starts crystallizing during a holding period at this temperature. The material freezes and starts to corroborate. While cooling down, the inner stress rises.

Because of the crystallization, the glass-ceramic core is much more heat resistant than a core that is made of glass. It needs more than 1100°C / 2021°F to fuse the glass-ceramic again, provoking leakage and material fail (see chapter 4.1).

2. REACTOR INTEGRITY WITH I&C FEEDTHROUGHS

Due to the importance of uncompromised integrity of a nuclear reactor, it is critical that the EPAs can withstand its conditions while maintaining electrical function. If EPAs are not able to withstand the same or even more severe conditions than the surrounding material, they can become weak points and are likely to fail during accident conditions. This is especially the case when aging organic materials like epoxy or PEEK are used in feedthroughs. PEEK polymers begin to weaken at temperatures of 260°C / 500°F and melt at 334°C / 633°F. These product characteristics increase the likelihood of malfunction, especially in demanding environments or in cases of fire.

Organic penetration assemblies were considered adequate in last century's nuclear power plant designs. The significantly higher severe accident integrity standards for today's reactors and higher temperature and pressure requirements of the HTR primary loop have created the demand for improved designs using glass-ceramic assemblies to withstand these extreme conditions.

Glass-to-metal EPAs have a maintenance-free lifespan of over 60 years, resulting in no outage time spent on these components. Glass-to-metal EPAs are an excellent choice for any reactor, especially when considering their lifetime costs in comparison with organic seals. Glass-to-metal EPAs therefore provide increased safety at a lower lifetime cost.

On a worldwide scale, EPAs have been installed in PWRs, HTRs, BWRs, and FBRs over many decades.

3. EPA STANDARDS

No maintenance is required for EPAs throughout the planned 40-year lifespan of the 210MWe HTR-PM. The HTR primary loop has very challenging conditions in which organic seals would fail.

SCHOTT has experience with HTR applications for the glass-to-metal feedthroughs from the 1960s onwards, including South Africa's pebble-bed modular reactor. Glass-to-metal feedthroughs have also been used in previous HTRs at Jülich and Hamm-Uentrop in Germany.

3.1 Glass-to-metal technology and manufacture

Glass-to-metal seals are comprised of inorganic, non-aging materials which have a virtually unlimited lifespan in high-temperature, high-radiation and high-pressure applications. They are proven, standard technology in other harsh environments such as nuclear submarines, automotive air bags, oil and gas applications, as well as high-pressure and extreme temperature applications like liquefied natural gas vessels.

Compression sealing of the components during manufacturing makes them extremely robust and suitable for the Shidaowan HTR-PM.

The principle of compression glass-to-metal sealing is based on the mismatch of the coefficients of thermal expansion (CTE) of the components:

CTE (housing) >> CTE (sealing glass) ≥ CTE (conductor)

This combination causes high compression of the housing onto the glass after the sealing process, shown in Figure 2.

The sealing process itself takes three steps:

(1) **Assembly of components on carbon fixture**
(2) **Heating to sealing temperature**: At sealing temperature, the molten glass fills the gap between the housing and contact.
(3) **Cooling to ambient temperature**: The glass re-solidifies. Due to the greater shrinkage of the housing, the solid glass is set under heavy compression.

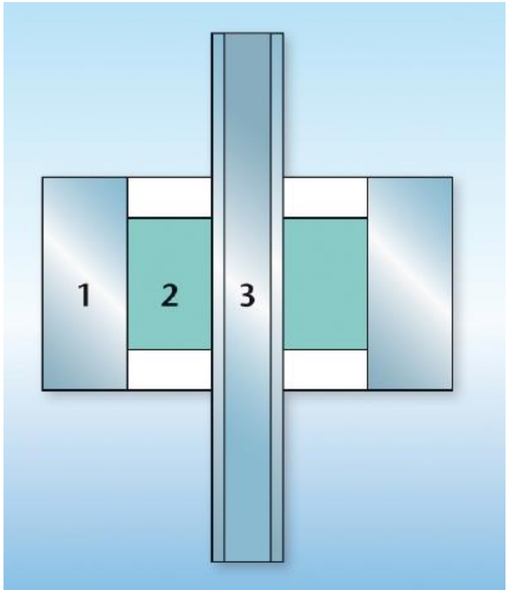

Figure 2. Schematic of glass-to-metal-sealed EPA, including (1) housing, i.e. carbon or steel; (2) sealing glass; (3) conductor, i.e. nickel or iron array

Glasses have a compressive strength 10 to 20 times greater than their tensile strength. This compressive force can be leveraged to improve the feedthrough strength by selecting metals for the housing with a coefficient of thermal expansion that is much higher than the value of the glass and interior conductor.

Due to this higher thermal expansion, the metal case shrinks firmly onto the glass during cooling to create a hermetic seal. Compressive load to the glass and conductor take place to such a degree that the metal remains pressed on to the glass, even if mechanical pressure is applied or there are major temperature changes.

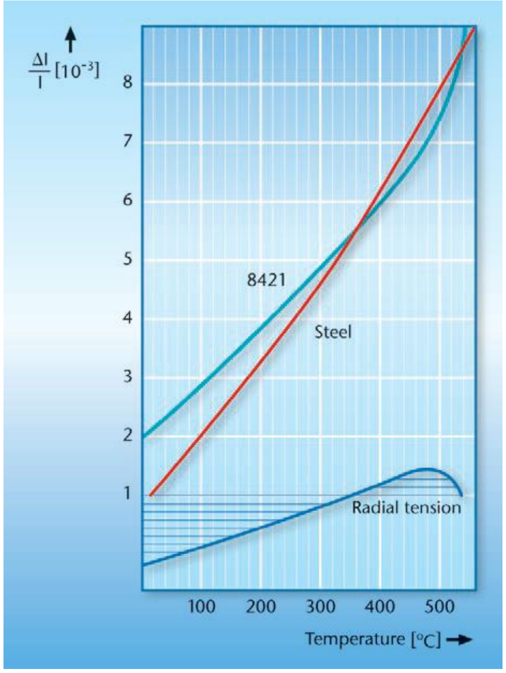

Figure 3. Relative thermal expansion of a glass (SCHOTT glass type 8421) and metal (compression ring) of a compression glass-to-metal seal.

3.2 Operational range of glass-to-metal EPAs

The feedthroughs have an operational range from (minus) -200°C to (positive) 350°C and are fully maintenance-free. They are suitable for applications in harsh environments where resistance to high pressure, temperature and radiation is required, and rapid changes in these conditions are a possibility. The capabilities and specifications are verified by thorough qualification tests performed by German regulators, and Wyle Laboratories in Huntsville, Alabama, USA.

They have up to 60 years qualified lifetime for the EPA with unlimited lifetime for the pressure boundary and exceed current severe accident standards, including pressure and radiation requirements in accordance with IEC/IEEE 60780-323, Ed. 1.0, 2016 [1]. The Shidaowan HTR standards include an operating temperature of 150°C, pressure of 70bar and radiation levels of 3.5MGy.

Table I. Specification of SCHOTT EPAs

Qualification Characteristic	Value		
Working pressure	7.0MPa	70bar	1015psi
Design pressure	8.1MPa	81bar	1175psi
Test pressure	10.5MPa	105bar	1523psi
Environment inside pressure boundary	99.9% helium		
Operating temperature	150°C	302°F	
Leak rate	$\leq 1 \times 10^{-8}$ Pa/m³/s	1×10^{-7} mbar/l/s	7.6×10^{-8} Torr/l/s
Integral radiation dose over installed	$\leq 3.5 \times 10^{6}$ Gy		

life			

Glass-to-metal EPAs have many characteristics that can make them a better option than organic seals. Among the most important of these are high electrical insulation; a hermetic seal; pressure resistance; chemical resistance and protection against corrosion; and a wide range of service temperatures.

They also have mechanical stability; fire resistance; flooding resistance; good heat conductivity, grounding and electromagnetic shielding; narrow tolerances; low-loss transmission; suitability for joining connections using specially-designed connectors; and easy installation and removal of feedthroughs to the header plate by means of metal seal rings.

As EPAs are able to withstand conditions in the primary loop of the HTR-PM, it means they exceed safety requirements in any reactor containment penetration application. They also have no costs associated with ongoing maintenance during expensive outage periods or any need for replacement during reactor lifetime.

4. THE SHIDAOWAN HTR PROJECT

Jiamusi Electric Machine Co., Ltd. and Chinergy Co., Ltd. (a joint venture between Tsinghua University and China Nuclear Engineering and Construction Group) chose to use SCHOTT glass-to-metal-sealed EPAs for the primary loop applications at Shidaowan HTR-PM in Shandong Province, China.

The end user is operator Huaneng Shandong Shidaobay Nuclear Power Co., Ltd. and the owner is China Huaneng Group.

The scope of the supply is EPAs for I&C applications: 64 electrical glass-to-metal feedthroughs for control rods and absorption ball, and 8 electrical glass-to-metal feedthroughs for helium blowers. They will contain and protect low and medium voltage I&C cables ranging from three-pin to 160-pin feedthroughs that exceed severe accident standards.

The HTR has a power rating of 500MWt, 210MWe gross and 200MWe net with a projected lifetime of 40 years, during which time the EPAs will require no maintenance.

4.1 Crystallizing glass-ceramic EPA in the HTR

At room temperature, a compression seal is defined by the compression of the ring onto the glass insulator. In case such a compression seal is heated again, the compression is reduced because the outer metal part has a higher thermal expansion coefficient than the glass. The inversion temperature is defined as the temperature at which compression is reduced to zero.

At even higher temperatures, tensile stress would be introduced into the glass-to-metal seal, which would lead to a detachment of the seal and subsequent leakage. Therefore, operating temperatures above the inversion temperature of the compression glass-to-metal seal must be avoided and ultimately limit its applications.

Further enhanced EPAs utilizing crystallized glass-ceramic material are used for co-axial EPAs in the HTR.

In this type of EPA, there is constant compression over the entire temperature range, including severe accident temperatures, which ensures full pressure resistance at all temperatures. There is no inversion temperature, which guarantees a hermetic seal at high reactor temperatures.

These positive properties of glass-ceramic material were also proven by scientific research [2]:

"In general glass-ceramics are proven to be superior in their mechanical properties in comparison to their glassy counterparts. Glass is characterized by its amorphous structure and the absence of grains and grain boundaries in the microstructure. Upon ceramization, three-dimensional crystals grow in the glass-ceramic that yield to a strengthening of the material. For example, Heydari et al. (J. Mater. Sci. Technol. [2013] 29 (1) p. 49-54) have shown in a similar glass family that the transformation of the glass into a glass-ceramic is accompanied by a three-fold increase in bending strength and an 8-fold increase in fracture toughness. "

SCHOTT makes use of its knowledge from the development of specialty glass and ceramics for the field of EPAs with crystallized glass-ceramic. The crystalline glass-ceramic, which was initially invented for solid oxide fuel cells (SOFC) with operating temperatures between 600 – 900°C / 1120 – 1652°F and aggressive environmental conditions within the cell (oxidant, humidity, fuel), is now utilized for the latest generation of EPAs.

5. OTHER APPLICATIONS

Due to the significant safety performance enhancements they offer, the EPAs have also been chosen by BWXT for its mPower SMR prototyping. The mPower SMR first loop requirements are an operating temperature of 320°C and operating pressure of 140bar. The SMR requirements are very challenging but are met by the new components, which will help form a strong I&C safety chain in future mPower SMRs.

Fields of application are not limited to the nuclear industry. The latest generation of EPAs is also suitable for any other application in which high temperatures and/or high pressures are given circumstances. Deep-sea activities such as oil drilling – with pressure levels in excess of 3500bar and temperatures above 200°C – are one example of an application well-suited for EPA integration. Usage in this safety-critical environment is another example of the high-stress capabilities of glass-to-metal seal technology that provides additional safety margin in case of a severe accident.

5.1 Cables and other I&C network applications

Technology enhancements that meet severe accident standards also include MI cable connectors, which form part of the functional chain of severe accident equipment needed to measure pressure, temperature and hydrogen concentration. Cables used for this equipment chain must be made of inorganic materials.

By comparison, standard Class 1E cables made of PEEK insulation will degrade at temperatures above just 230°C and melt at 334°C. Organic seals and cables do not withstand future severe accident temperature and SMR core requirements.

CONCLUSIONS

Glass-to-metal EPAs have been chosen for the Shidaowan HTR-PM because they are extremely robust and can withstand the temperature, pressure and radiation requirements of the HTR-PM primary loop.

The properties of the materials used in the EPAs together with specialized manufacturing processes create a component that has up to 60 years qualified lifetime, with unlimited lifetime for the pressure boundary. The EPAs exceed current severe accident standards, including pressure and radiation requirements, in accordance with IEC/IEEE 60780-323, Ed. 1.0, 2016 [1].

Over the lifetime of a reactor, the inorganic materials used in the EPAs will not age, resulting in a low overall cost and preventing any outage time related to these components. They are therefore ideal for any reactor containment penetration application and have also been used in mPower SMR prototyping.

The HTR-PM primary loop environmental conditions preclude the use of EPAs with organic seals, since they are not capable of sustained performance for the lifetime of the plant and the harsh conditions present within.

Since glass-to-metal-sealed EPAs have an operational range from (minus) -200°C to (positive) 350°C and are fully maintenance-free, they are an excellent choice for the HTR-PM primary loop environmental conditions.

Enhanced technology such as crystallized glass-ceramic EPAs and the use of MI cable connectors can further improve the performance of key I&C network components.

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