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Material Selection for Cable Gland to Improved Reliability of the High-hazard Industries

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Abstract. The sealed cable glands (SCG) are available to ensure safest connection sheathed single wire for the hazard production facility (nuclear power plant and others) the same as pilot cable, control cables, radio-frequency cables et al. In this paper, we investigate the specifics of the material selection of SCG with the express aim of hazardous man-made facility. We discuss the safe working conditions for cable glands. The research indicates the sintering powdered metals cables provide the reliability growth due to their properties. A number of studies have demonstrated the verification of material selection. On the face of it, we make findings indicating that double glazed sealed units could enhance reliability. We had evaluated sample reliability under fire conditions, seismic load, and pressure containment failure. We used the samples mineral insulated thermocouple cable.

1. Introduction

Annual growth of atomic power stations that are being build and power supply units additionally brought into service in nuclear power stations (China, Iran, India, a new atomic station in Turkey) that are potentially hazard production facilities, results in increasing requirements of their functional safety. Different types of cable lines are used in nuclear and space industries to provide communication, power supply and control of power and nuclear plants, complex components, machines and vehicles, diagnostics of radiation-thermal condition of equipment components of hazard production facilities [1–4]. Solution of these tasks stipulates necessity to introduce pilot cables, radio-frequency cables, and control cables into the envelope of a hazard production facility. Cable glands are intended to provide tight cable introduction into the hazard production facility. They provide communication and information interaction of parts of the system or parts of different systems widely or nearly spaced.

Interaction of object parts is carried out via a great number of sealed cable glands of radio-frequency signals. Moreover, sealed cable glands are necessary for feeding circuits, for controlling and measuring inside the nuclear plants. Their operation provides key functions inside the reactor, and their insulation is to withstand pressure inside the nuclear containment. Organic polymers (epoxy resin) meet [1] general standards of insulation for sealed cable glands at nuclear plants of the first and the second generations. Experts in the sphere of nuclear power engineering are concerned that in case of severe accidents integrity of epoxy sealed cable glands can be damaged. Quality of technical condition of sealed cable glands, their efficiency characterized by the signal transfer ratio is critical when an emergency arises. It is exceptionally important to provide high stability of electrical, radiation, thermal, and thermodynamic elements – sealed cable glands (SCG) of pilot and power lines of power supply.
units of hazard production facilities [1,5]. This defines research objectives and analysis of tasks stated below.

2. Objectives and tasks of analysis
The problem of providing ideal transfer or close to ideal properties of sealed cable glands can be solved by means of searching a rational material composition and developing an optimum SCG unit design. Preceding long years of research followed stated results of searching ways and methods of solutions, procedures of variant choice that meet requirements and performance standards of reliability and SCG stability in critical and emergency situations at radiation and hazard facilities. In this paper, requirements for SCGs, research results and experience accumulated during development of reliable SCGs that are resistant to critical and emergency situations have been systematized.

3. Research fundamentals
Cable glands based on polymer compounds [5–6] are widely used nowadays. This tendency predominating in the world practice has some disadvantages. In particular, ageing processes take place under natural and artificial radiation. In operation conditions ageing action results in increase of mechanical stresses in polymer materials that cause material cracking, and as a result, loss of SCG tightness. In fire condition (extreme emergency), polymer components are subjected to inflaming when the temperature is above 300° C. It results in loss of sealing in SCG, loss of its durability and escaping of ionizing radiation fluxes into the environment that surrounds the nuclear plant. The search strategy of materials choice for elements of new SCG designs is determined by the engineering requirements based on their actual operating conditions in the structure of nuclear power plants. Increase of safety requirements of such objects (nuclear plants) results in establishing of particular specifications and their combinations in normative documents that regulate safety parameters for the containment systems and their components in case of non-project accidents. Imposing these requirements is reasonable, because SCGs are the components of containment systems that are critical for safety. Moreover, SCGs perform localizing and providing functions of technogenic-hazard object.

Main requirements imposed on materials in designing new radiation-hardened SCGs are high resistant to complex effect of ionizing radiation fluxes in a wide range of changes of environment effect in operational conditions of SCGs, to physical-mechanical actions of thermodynamic pattern, and also, to solution optimality of mass-dimensional indexes task.

Negative experience confirms this. Nuclear plant “Fukushima-1” in Tohoku region [6] was damaged by the 9-earthquake intensity on the Richter scale on 11 April 2011. This earthquake resulted in tsunami wave of up to 40.5m height. Tsunami caused catastrophes of three nuclear reactors of nuclear complex “Fukushima-1” where hydrogen explosion was recorded. This hydrogen accumulated beyond the outer reactor shielding after the cooling system failure.

Experts of the operator-company of nuclear plant “Fukushima-1” analyzed the accident and came to conclusion that in the accident, the temperature inside the protective shielding increased more than four times in comparison with the operating one. The design pressure exceeded more than two times. Exceptionally high level of temperature and pressure resulted in deformation of the whole set of epoxy sealed cable glands. This, in turn, caused leakage of highly explosive hydrogen. On completion of the investigation, it can be affirmed, that it was hydrogen leakage through the SCG that resulted to the explosion of “Fukushima-1”. This proves once more the fact that SCGs play a key role in providing object safety. Taking into account experience with “Fukushima-1” accident [6] that happened because of seismic cataclysm it can be stated that SCG material in some cases is to be resistant to a wide range of thermal shock loads arising in critical and emergency situations. In other words, characteristics of SCG insulating basis greatly effect on plant safety and reliability. During operation of a cable line with SCG ageing of polymer insulation accelerated by electromagnetic impact of current through the cable causes electro physical performance degradation [5, 6].

High power current in the cable line generates thermo- and electrodynamic of factors effecting on alteration of volume of SCG elements. Appearing small mutual shifts of contact surfaces of SCG elements caused by thermomechanical factors and electromagnetic impact of high power Ampere current in the line can be effectively diagnosed by means of differential methods [7–8] of optical and
laser engineering [9–11] with high or sufficient accuracy of measurement comparable with the wave length fraction of probe radiation. Propagation of damaging action of thermodynamic factors and mechanical deformation of SCG elements results in material properties destruction and rise of acoustic emission effect that can be recorded by means of developed methods of acoustic diagnostics [12].

Briefly, the essence of main requirements is the following [1, 4, 6], SCG is: to have higher radiation resistance under action of gamma-radiation (accumulated radiation dose average on great number of accidents ≈5·10⁸ rad); to consist of incombustible materials having chemical resistance under high temperatures (standard fire mode – up to 990°C); to withstand action of decontamination fluids and to meet natural conditions of corresponding State Standards.

To solve the problem of material radiation resistance, analysis of current condition of material properties research suited for SCG has been carried out. The results of large quantity of different authors’ papers have been taken into account [1–10]. Moreover, research carried by the authors in cooperation with the group of scientists of Institute of Nuclear Physics of Uzbek Academy of Sciences. Results of generalized analysis of practical operation conditions of SCG and in the best interest of ionizing radiation factors effecting on material properties in critical situations displaying data for determination of extreme parameters of SCG operation modes are shown in the table 1.

| Parameters                              | Normal operation mode | Heat removal disturbance mode of the pressurized area | Minor leak mode | Maximum leak mode |
|-----------------------------------------|-----------------------|------------------------------------------------------|-----------------|-------------------|
| 1. Temperature, °C                      | 15-60                 | < 75                                                  | < 90            | < 150             |
| 2. Pressure (discharging) MPa (atm)     | 0,85-0,103 (8,5-1,03) | 0,05-0,12 (0,5-1,2)                                   | 0,17 (1,7)      | < 0,5             |
| 3. Humidity,%                           | 90 at T=60 °C         | 100                                                  | Steam-air mixture | Steam-air mixture |
| 4. Specific activity Ci/L (Bq/L)        | < 2·10⁻⁶ (7,4·10⁴)    | < 2·10⁻⁶ (7,4·10⁴)                                   | < 1,5·10⁻³ (5,56·10⁶) | < 2,5 (9,25·10¹⁰) |
| 5. Absorbed dose rate, rad/h, Gy/h       | < 100 (1)             | < 100 (1)                                            | < 100 (1)       | < 10⁵ (10⁵)       |
| 6. Mode action time, h                  | –                     | < 15                                                 | < 5             | < 10              |
| 7. Rate of mode occurrence              | –                     | Once a year                                           | Every other year | Once a life time  |
| 8. Post-accident temperature, °C        | –                     | –                                                    | < 60            |                   |
| 9. Post-accident pressure, MPa          | –                     | –                                                    | 0,05-0,12       | 0,05-0,12         |
| 10. Action time of post-accident modes, day | –                     | –                                                    | 30              | 30                |

4. Aspects of rational material choice

While analyzing properties of different materials, it is possible to come to conclusion that owing to specific character of chemical bonds some materials are not virtually affected gamma-radiation factors. These materials are copper, steel, nickel, molybdenum, solders based on copper and silver. These materials are radiation-resistant. Property of radiation resistance means that it is possible to use these materials for a long period under any gamma-radiation dose. Therefore, radiation-resistant solders based on copper and silver were chosen for designing of SCGs for nuclear power plants.

In SCGs designed by our group, cables with copper current-carrying conductor and electrical insulation based on magnesium oxide of MICSC (mineral insulated copper sheathered cable) type have been used. SCGs use thermocouple cables with mineral insulation and current-carrying conductors of alumel and chromel. Besides, cables with mineral insulation of MICSC type have copper or steel shell, and some current-carrying conductors sealed with magnesia insulation against the shell are inside this shell. Such radiation-resistant and mechanically-resistant cables are unaffected by burning (they resist temperature up to 1000 °C). When choosing insulating materials, three groups
of materials were researched: ceramic materials, materials having glass components, and polymer-based materials. Among the mentioned materials, the following ceramic insulating materials have rather high radiation resistance: magnesia and high-aluminous ceramics, steatites and porcelains. Electro-technical glass has similar properties.

When analyzing opportunity of developing practical SCGs, the fact was taken into account that nowadays polymers are widely used in SCGs. Polymers are used for sealing ends of cable modules and for tight connection of cable modules with SCG flanges. Structures using polymers have some disadvantages. SCGs are subjected to gamma-radiation, oxygen, moisture, air, mechanical and electrical stresses, and thermal action. Gamma-radiation impact on polymer materials in combination with listed factors accelerates negative processes happening in polymers. With time, sealing units lose their tightness under gamma-radiation because of wide range of processes taking place in polymer components. These processes include: destruction, crosslinking, intramolecular bond formation, decomposition and formation of conjugate double bonds, radiation oxidation, and crystallinity change. Free radicals having increased activity are also formed. Polymer materials radiation happens in the medium of very active chemical element – oxygen. Combined action of these factors results in decreasing mechanical strength and accelerates destruction, and as a result, break of polymer molecule chains and breaks of internal and intermolecular chemical bonds in cross-linked polymers [1]. Crosslinking, radiolysis and destruction processes are followed by element volume alteration, making it brittle, gas products emission. All this taken together results in loss of tightness. Besides, using cables with polymer insulation inside the sealed volume of sealed cable glands, long-term gamma-radiation action to polymer insulation results in pressure increase due to radiolysis gas products. In the paper [1] it is mentioned, that the lifetime of polymer materials under simultaneous action of gamma-radiation and high temperature is far less than the lifetime under the same, but successive actions. Gamma-radiation of polymers accelerates post-radiation processes caused by reactions of trapped free radicals. As an absorbed dose increases, crosslinking rate also increases. At the same time accumulation of fragments of disrupt molecules takes place, this worsens material properties and results in its destruction. Gamma-radiation do not practically influence on glass, ceramics and metals in contrast to polymers. Glass sealing in SCGs has some disadvantages – it is poorly protected from mechanical action that causes loss of tightness of a unit. Figure 1 shows overall view of the SCG based on thermocouple cables with mineral insulation.

![Figure 1. Sealed thermocouple cable gland.](image)

Having analyzed practical and theoretical research of above mentioned three groups of materials and having compared given $\gamma$-radiation doses after exceeding of which substantial decreasing (by 25%) electro-physical material properties starts (for ceramics, glass and metals), it is possible to come to conclusion: radiation resistance of ceramics and metals is incomparably higher than of polymer materials.

In the process of reasonable choice of terminal cable ceramic insulators for test samples of sealed cable glands research of some kinds of metal-ceramic units (MCU) based on high-aluminous ceramics microlite were performed. MCUs have been researched before and after gamma-radiation action by $5\times10^8$ rad dose in a steam-air medium adding decontamination mixture at temperature 150 °C and pressure 0,5 MPa. As a result of research, it has been found that MCUs based on ceramics of Microlite type provides higher vacuum tightness (up to 85%) in comparison with MCUs based on ceramics, where vacuum tightness is lower (by 7–8%). Electrical resistance of MCU insulation under normal conditions is rather high $5\times10^{15}$–$5\times10^{19}$Ohm. After gamma-radiation action by $5\times10^8$ rad dose magnitude
of electrical resistance of insulation medium changes slightly. If MCUs are placed into a steam-air medium and in case of creating modes of large and small break accident, MCU resistance falls dramatically up to $10^5$–$10^6$ Ohm, at the same time MCU completely keeps its tightness. Following the research, it has been found that metal-ceramic insulators based on Microlite have higher characteristics. For high reliability of components and, in general, for SCG construction, components based on MCU [1, 13–21] have been chosen.

Metal-ceramic module is rather simple. It consists of a ceramic tube hermetically soldered with front and rear cuffs. The front cuff is hermetically joined with an input cable conductor, and the rear cuff is joined with an output cable shell. In the developed SCG thermocouple cables KTMC(XK)-2x0,9 or KTMC(XA)-2x0,9 are used. Cable ends are sealed with two-channel metal-ceramic insulators or glass tablets made of glass-ceramics. The equivalent circuit model to measure electrical characteristics of the SCG is demonstrated in Figure 2.

![Figure 2](image_url)

**Figure 2.** The schematic diagram of connections to qualify rating SCG and to determine the level of interfering signal in single conductor screened cable: $V$ – voltmeter to measure voltage drop (interfering signal); $U_{in}$ – test signal voltage; $U_n$ – drop voltage due to the interfering signal through circuit resistance; $C_r$ – cable capacitance per length; $Z_n$ – impedance of the measuring circuit for interfering signal.

Some experimental results obtained during the research of electrical parameters of SCG are shown in the Table 2.

| Cable type     | $C_m$, pF/m | $\tan \delta$ | $Z_n$, Ohm | $\alpha$, dB/m | $(\varepsilon_r)^{1/2}$ | $\varepsilon_r$ |
|----------------|-------------|---------------|------------|-----------------|-------------------------|----------------|
| MICSC-1x4      | 475         | $8 \times 10^{-4}$ | 15         | $10,4 \times 10^{3}$ | 2.15                    | 4.6            |
| MICSC-7x2.5    | 228         | $16 \times 10^{-4}$ | 32         | $4,5 \times 10^{3}$  | 2.20                    | 4.8            |

Calculated values of electrical parameters of MICSC-1x4 cable and SCG are obtained by means of methods stated in [1, 22–23].

For SCGs of SPCG type (sealed pilot cable gland) different steels have been used (for example, Steel-3), solders based on copper and silver, cables with copper or steel shell and mineral insulation (type MICSC), ceramic insulators. These materials have high radiation resistance. Moreover, they have high fire resistance, in contrast to polymers decomposing at high temperatures and releasing toxic substances. In addition, the materials are protected with special coverings with high resistance to action of damp tropic climate and decontamination solutions.

5. Conclusion
SCG based on metal-ceramic materials and cables with mineral insulation have enhanced heat stability under radiation and other emergency factors. The method to evaluate an effect of an electromagnetic field to parameters of circuits with SCG pilot cables of MICSC type has been developed. It has been proved that electrical parameters of MICSC type cables permit using them in SCG pilot cables at technical high-hazard objects.

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