Measurement of the High Gamma Radiation Dose Using The MEMS Based Dosimeter and Radiolisys Effect

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MEASUREMENT OF THE HIGH GAMMA RADIATION DOSE USING THE MEMS BASED DOSIMETER AND RADIOLISYS EFFECT

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***Abstract* — The measurement of high and very high doses of ionizing radiation is crucial for the monitoring of the existing Nuclear Power Plants (NPP) and high energy physics facilities as Large Hadron Collider (LHC). All of the structural materials exposed to such high gamma doses are continuously damaged and their mechanical properties are strongly affected. The constant monitoring of the absorbed dose is then crucial in order to assure safety operation of these facilities. In this paper we present the new technique of such a measurement using simple MEMS transducer and phenomenon of polymer radiolysis.**

***Keywords :* Radiation dosimeter, polymer radiolysis, MEMS**

I - Introduction

As there is more than 400 operating Nuclear Reactors in the world and about 50 under construction, we are all concern about the safety operation of these facilities. One of the major problem that has to be taken into account during the reactor design is the material aspect of the structural design. It has to be said that the operating environment is extremely harsh due to the high temperature (about 300°C in today's reactors and about 800°C in the future ones) and high radiation dose. If we consider, that the average time of exploitation is estimated to be 40 years and very often is increased by additional 20 years, we can easily imagine how robust the design of the nuclear reactor should be. It is obvious, that most of the issues concern materials as their parameters change due to the cumulative absorbed dose. Needless to say that the typical NPP of 3rd generation (relatively modern design) is equipped with about 10000 sensing units including temperature monitors, pressure transducers, humidity sensors and , of course, radiation detectors and dosimeters.

On the other hand, we are building new research infrastructure for high energy physics as a LHC at CERN. As we want to achieve greater energies, the greater radiation doses occurs at the facility what causes mostly similar problems that occurs at NPP. Moreover, newly designed future facilities will operate at much higher energy levels and thus, higher radiation doses that will occur during normal operation.

At the figure 1 we can see the doses of gamma radiation that occurs inside reactor vessel of the research reactor at SCK-CEN in Belgium.

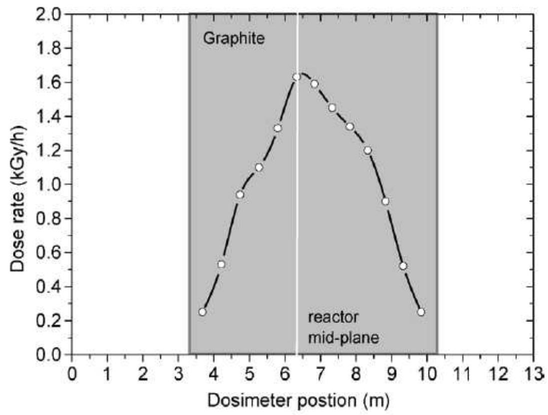

Figure 1*: Gamma radiation dose inside the vessel of the research nuclear reactor in Belgium. Courtesy of SCK-CEN*

What we can clearly see is that radiation doses at the walls of the reactor is estimated to be about 0,2 kGy/hour what is a very high value. One Gray [Gy] is a unit of absorbed dose which corresponds to 1J of energy absorbed by the 1 kg of the matter. By doing a simple calculation, we can compute the annual cumulated dose on which the reactor walls will be exposed which is estimated to be 1,75 MGy. In order to compare, the typical dose used in photon radiotherapy varies from 40 to 80 Gy for the whole therapy which lasts 1 to 2 months.

Another interesting example of high dose occurrence is the LHC. On figure 2, we can see the cross section of the collider with cumulated gamma doses in Grays in different regions of the tunnel.

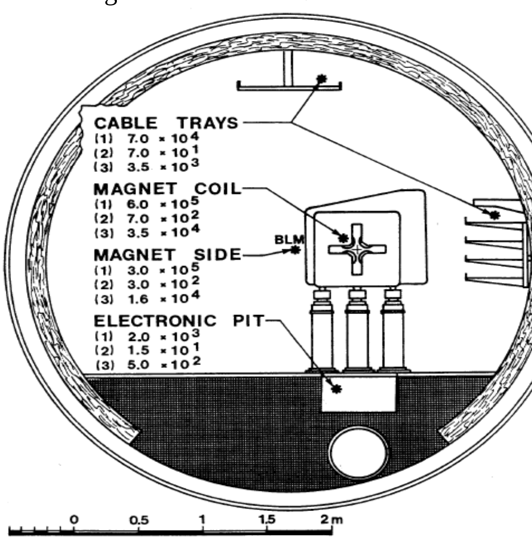

Figure 2*: Cumulated(1976-1986) gamma dose in the LHC tunnel. Courtesy of CERN.*

It has to be emphasized, that the dose value at LHC was cumulated over 10 years what shows us, that the dose intensity is much lower than in nuclear reactors. Nevertheless the reason for that is the operation mode of the LHC where the experiments are performed a few times a month, so the actual intensity of the dose during the experiments may be actually higher than in the NPP. It is then clear that the need of the measurement of the radiation dose at the levels of 1MGy exist. The current methods of the measurement of such high doses uses the different types of passive dosimeters such as thermo-, radio- and photoluminescence indicators or hydrogen pressure dosimeters. Each of them has drawbacks and advantages depending on the application but the major problem in all types of these dosimeters is complicated readout (spectrometry, electron-spin-resonance, etc.) that has to be performed AFTER irradiation and OUTSIDE of the radiation zone using specialized equipment. It is caused by the impossible use of electronic circuits as they fail above 10-20 kGy range. Thus, for low or medium doses, the solid-state MOS based sensors are used.

In this paper, the MEMS based solution using well known principle of hydrogen pressure dosimetry is presented.

II - Experimental Details

One of the method of measuring high radiation doses is so-called hydrogen pressure dosimetry. The principle of the method is based on the radiolysis phenomenon. It was shown that polymers releases gases due to the ionizing irradiation. The amount and composition of the gases depends on the polymer and by analyzing we can see that the polyethylene is quite an interesting material.

Polyethylene, by its simplicity contains only Carbon and Hydrogen atoms. As the hydrogen binds are weaker than the carbon binds, the radiation energy breaks the binds and releases free hydrogen atoms. Of course, a lot of polymers have a different composition because of some additives but according to literature data, polyethylene releases mostly hydrogen (85-95%). It is also shown that depending on the experiment conditions and material the radiation yield (so-called G factor) may differ from 2 to 7. The $G(H_2)$ factor is defined as a number of hydrogen molecules released by 1g of polyethylene after absorbing of 1eV of the energy. As the absorbance/exposure factor for polyethylene is very close to 1 we can say that the 1eV of the absorbed energy equals to about 1,6e-17 J per 1 g, so about 1,6e-14J per kg which means 1,6e-14 Gy.

This principle is used in hydrogen pressure dosimeter where the LDPE (Low density Polyethylene) foil is put inside the vacuum glass chamber and then pumped out and sealed. After radiation exposure, the chamber is open in controlled atmosphere and the gas analyzer calculate the amount of hydrogen and thus, the absorbed dose. The main drawback of the system is its small sensitivity to the low doses as the volume of the glass chamber is huge in comparison to the amount of hydrogen. Thus, the effective dynamic range of the measurement of the HPD starts at 10kGy.

What we present in this paper is a way to introduce hydrogen pressure dosimeter into micromechanics in order to have a small passive sensor with easy readout and bigger dynamic range starting at lower doses.

The main idea is to build a microchamber that will be filled with polyethylene and closed from one side with a thin membrane. Due to the outgassing of material inside the chamber, if the chamber is hermetically sealed, the evolving gas will increase the pressure inside the cavity what will results in membrane deflection and in extreme case in membrane fracture. The figure 3 shows the basic structure of the sensor.

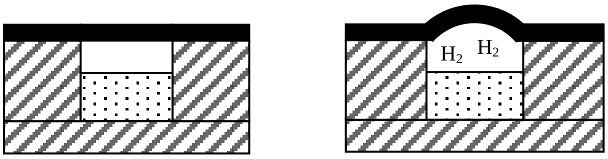

Figure 3*: Basic principle of hydrogen pressure MEMS dosimeter.*

As we can see, the structure of the sensor seems to be simple, but in reality there is a lot of problems that should be taken into consideration during the design and fabrication stage.

First, from the designer point of view, a proper membrane design has to be chosen depending on the proposed readout technique and operating mode. The operating mode may be both: incremental one ore the threshold one. In first, when the cumulated dose will incrementally increase the pressure inside the cavity, the dose will be measured by the corresponding membrane deflection. In the second mode, the membrane will fracture at some pressure level that generates critical stress inside the membrane.

The incremental modes should be used in order to have the direct measurement over the time and during normal operation. The threshold mode may be used when we want a fast indication of certain level of the absorbed dose i.e. for incidents monitoring. According to the literature, the incident monitoring should allow us to measure as high dose intensities as 50kGy per hour what is an extreme dose and the exact dose value is not so important.

A. Design considerations

The amount of hydrogen released by polyethylene due to its irradiation may by calculated by using he radiation yield factor and by assumption that all of the calculation will be performed for normal conditions (room temperature and atmospheric pressure). Let us take the most common G factor value for HDPE (high density polyethylene) which is equal to 6. Let us assume also that the absorbed dose of the polyethylene is equal to 10kGy. By definition, it means that for 1kg of HDPE, the absorbed energy is equal to 10kJ or 6,24e+22eV. Then (from definition the radiation yield) for each 100 eV HDPE releases 6 molecules of hydrogen. For our case it gives us about 3,74e+21 of H_2 molecules. If we consider that 1 moll consists of 6e+23 of molecules, we will generate about 0,0062 moll of H_2. In normal conditions, the volume of such amount of gas will be equal to 139 cm^3. All above mentioned calculations were made for 1 kg of HDPE, (apart from G factor) so we need to divide the result by 1000 in order to find that the amount of hydrogen released form 1g of HDPE due to gamma irradiation of 1kGy is equal to 0,14 cm^3. If we consider the density of HDPE which may be estimated to 0,95 g/cm^3, we can easily see that the volume of evolved gas for 10kGy of radiation equals to 14% of the HDPE volume. Taking into account the fact, that the resulting increase in pressure inside the sealed cavity will depends not only on the volume of the released gas but rather on the ration between evolved gas and free space inside the cavity, we can easily imagine that the dynamic range of the dosimeter and its sensitivity for medium doses may be increased by using the micro-technology and small cavity sizes.

Let us see how this quantities may transduce into the mechanical behavior of the membrane. We designed a structure where a square membrane witch was 4,9 mm wide and 30 µm thick. The HDPE cavity size was a square shaped cavity which was 5 mm wide and the HDPE layer was about 350 µm thick. The free space over the cavity was 12 mm x 5 mm x 30 µm as we designed the three membrane threshold detector (figure X).

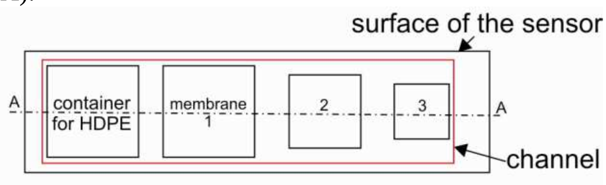

Figure 5*: The top view of the designed structure.*

After the fast calculations using Timoschenko's plates and shells theory (what we can do as the wide over thickness ration for our membrane is high), we can easily calculate, that for 10 kGy of absorbed dose, the increase in pressure inside the cavity should be equal to about 0,65 bar which will result in membrane deflection of about 384 µm which is not really true as we are above the regime of small deflections but it gives us the idea about the possible sensitivity of the sensor. The resulting maximal stress is estimated to be about 0,48 GPa so if we consider the minimal reported yield strength if silicon, our membrane may brake at about 1 GPa so above 21kGy.

B. Technology considerations

The basic layout of the structure is presented on the figure below (figure 6). For the reason of process simplicity, we decided to put the HDPE in a one cavity, and have the other cavity with the membrane for readout. Both cavities are connected by the thin channel. It is caused by the difficulty to fill the exact amount of HDPE with good control of the free space of the volume. Therefore, one cavity is filled almost full with the HDPE and the thin channel and design of the second cavity decides about the free space volume and thus on the sensitivity of the sensor.

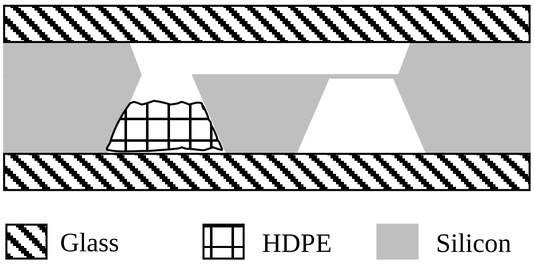

Figure 6*: The cross section of the designed structure with one membrane and one HDPE cavity.*

The sensor is a multistack glass silicon bonded structure. Such a type of bonding were chosen as it assures hermeticity at low bonding temperature which is crucial for polymer inside the cavity. The membrane and cavities are made of n-type (100) silicon that was wet etched by KOH solution. Such a structure were anodically bonded to Schott 33 glass and then the HDPE was put inside in inert atmosphere in order to avoid oxidation of HDPE that limits the rate of evolved hydrogen. After the HDPE filling, the whole structure was closed by second anodic bonding at lower temperature (about 300°C) in order to prevent polymer from its decomposition. Everything was done in inert atmosphere and a pressure slightly lower than the atmospheric pressure.

III - Results and Discussion

A test samples of the dosimeter were fabricated according to the design presented in previous paragraph. Two sensors were irradiated with using the particle accelerator at National Centre for Nuclear Research. Two main types of radiation were used: direct electron beam with the energy of 6MeV and spot size of about 3 mm, the gamma beam produced via conversion target mounted at the end of the accelerator. The gamma beam due to its conversion had a peak energy of 4 MeV and was a dispersed beam. It means that electron beam was focused only on the HDPE cavity whereas gamma beam covered whole sensor die.

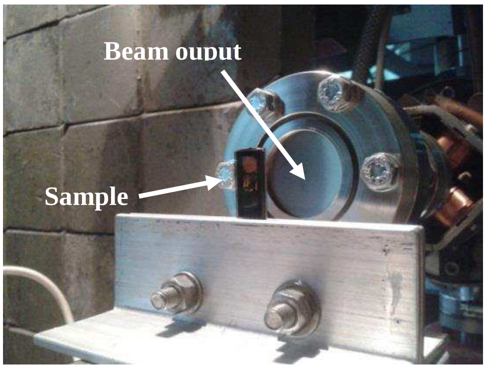

Figure 7*: Test set-up for irradiation of dosimeter with the particle accelerator.*

The irradiation test bench (figure 7) was calibrated using the ionization chamber. As the high intensity dose may seriously heat the sample, in order to avoid that, adequate repetition rate was applied. The irradiations were performed for the dose range from 10 kGy to 120 kGy. As our sensor was built with 3 different membranes, we could see the consequent membrane ruptures starting from the biggest membrane. Thus, we observed the threshold mode of sensor's operation. Table below shows the measured doses which causes the destruction of the first two membranes.

Table 1: *Value of doses at which two first membranes fracture occurred*

	Membrane 1 fracture [kGy]	Membrane 2 fracture [kGy]
Sample 1	26,4	81,9
Sample 2	25,6	102,4

As we can see, the first membrane fractured at similar dose for both samples whereas the second one broke at different doses. The figure 8 shows the sensor after first membrane rupture.

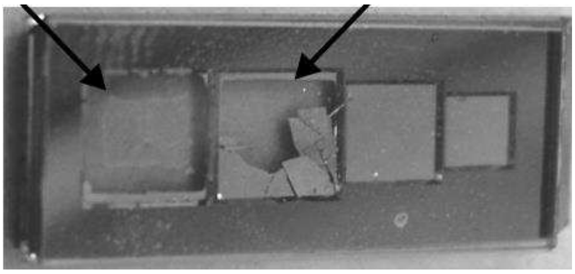

Figure 8*: A sensor structure after irradiation and first membrane rupture.*

It has to be said that the rupture mechanics of the membranes, especially those made of crystalline silicon is not an easy process and there are a lot factors contributing to the critical stress that membrane can withstand. For example the data about yield strength for crystalline silicon varies from 1 to 20 GPa what is a result of multiple effects that have to be taken into account. For example for KOH etched membranes, as it is in our case, may be broken quite easily if they have rough surface or some etching defects that are the stress concentration regions. The stress concentrated in a small volume may cause the microcrack which will propagate over the volume and damage the membrane. The other factors that may affect the mechanical durability is doping and the quality of the silicon.

All above mentioned facts may lead to the conclusion that the threshold mode is quite useful for the rough dose estimation as there is a lot of factors that may be difficult to reproduce and the quality control will be the major issue in case of further product development. Nevertheless, for accidents monitoring where extremely high dose intensity occurs and the exact dose is not a crucial issue, the threshold operation mode, due to its simplicity may be an appropriate solution.

In the future work, the measurement of the membrane deformation will be measured in order to verify how the incremental operation mode works. Needless to say that for perspective use of the device, the stability of the measurement will be crucial. One of the factor that may limit the operational use of the sensor is hermeticity of the cavity. We then took one sample and irradiated it with a dose of 10kGy in order to observe the deformation of the membrane in time. It was not possible to measure the exact membrane deflection, but it has to be said that after a few months the membrane is still deformed so we may assume that there is no big leakage at the bonding interface but without future investigation it is not possible to tell more about this issue.

IV - Conclusion

We presented the potential method of high radiation dose measurement using relatively simple technique. It was presented that the fast and simple method of monitoring of high doses is necessary in order to improve the safety procedures in NPPs and high energy physics infrastructure. We presented the design and technological considerations that have to be taken into account during the design phase. The experiments that were performed showed that such an approach may be used to monitoring a high radiation doses. It is clear that a lot of work has to be done in order to characterized the system, especially the membrane deformation in a function of the absorbed dose thus, the future investigation are ongoing. Another major issue that has to be addressed is the technology that has to be checked for its long term stability in terms of hydrogen leakage from the structure.

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