Role of Sensors (Nano) in Nuclear Technology

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Abstract. Sensors in a nuclear plant required to be highly accurate, could sense and transfer the process variables at high speeds, provide timely display, Sensors relate with nuclear plant’s processes to measure several parameters such as gas leaks, high temperatures, pressures and flow levels, monitor radiation, chemical and biological nuclear sensing, concentrations of gases and components of safety that process the data enabling on-site/on-line monitoring. Special instruments also measure vibrations, H₂ concentration, and conductivity of water, meteorological and concentration or other applications. For example, resistance temperature detectors those are significant to the safety system of the plants[1], with predictable accuracy and respond to changes in temperature in less than 3 seconds. Emerging sensors for the core plant technology has continued the same from their commencement, though several novel sensor technologies have been developed and prototyped, could find adoption in the next-generation nuclear power plants. The next-generation reactors may require extremely high temperatures accurate measurement and this could be the technical challenge that was facing today’s novel sensor development. In this presentation, the author discusses sensors, types, miniaturisation towards nanosensors, why we need to measure, their characteristics, classification with a specific set of applications followed by summary and conclusions. Combining these smart nanosensors with virtual reality / AI with available systems based on nanostructured electronics wireless sensor networks could enable more and more effective functionalities.

1. Introduction
Sensors were part of modern day’s comfort living and built into many medical devices, electronic devices, automobiles, smart offices, houses, security and plant safety systems and prototypes for monitoring harsh gaseous and environmental conditions. Such applications mandate miniaturization - reduce the size, power consumption and to be integrated into portable devices. Nanotechnology has a wide range of implications for all the areas, potentially providing stronger, lighter materials, smaller, smarter, materials, components and new sensor technologies. The application of nanotechnology via
nanomaterials and nanostructures to sensors allows overwhelming response in flexibility and performance. To name a few technologies, new sensor technology combined with micro and nanofabrication technologies can deliver a wide range of applications with much-reduction in size, networking, less energy usage, also enabling maximum integration of ‘nanosensors’ into many other devices. These nanosensors have high selectivity, sensitivity, and stability and can be used as a new range of sensors for harsh environments.

Sensors play a key role in mankind safety, monitoring and comfort. The sensor also exists in a variety of forms for several purposes. In case of nuclear safety and security sensors aid in nuclear waste treatment & storage, gas leaks, temperature monitoring, humidity monitoring, corrosion monitoring, for fault monitoring, nuclear reactor protection, safety, monitoring temperatures, humidity, radiation, basic research, physical protection system (PPS) function is to meet three basic elements detection, delay, and response and even in case of sabotage.

2. Gas and Volatile Sensors

Sensors based on nanocrystalline materials[2] are used in harsh environments for detecting trace/ultra-trace gases and volatiles. For monitoring H₂ concentrations of 10-15 ppb under regular operating conditions of a nuclear reactor and in the presence of high-pressure steam, a sodium electrochemical hydrogen meter[3] was used. H₂ was also monitored under low power operating conditions with a detection limit of 30 ppm and at T₉₀ ~ 250°C. The usage in fast breeder reactors, liquid sodium as a coolant is safer, due to electrochemical hydrogen meter[4].

Standard, reliable oxygen sensors usually based on Yttria-doped thoria. Portable oxygen sensors were manufactured by a simplified manufacturing method (co-firing) for laminated ceramic sheets. Yttria-stabilized zirconia (YSZ) and Yttria-stabilized zirconia/cordierite composites for the porous layer type sensor, as a solid electrolyte and as a diffusion barrier, respectively. The sensors are made up of as a monolithic body holding patterned heater[5] using a lamination process. Paper-based oxygen sensor, a simple prototype made from a ZnO crystal film, readily dispersed on the surface of the paper. Using UV illumination over the sensors photoconductive surface, UV light produces oxygen desorption causing current variations in the sensor. These variations are directly proportional to the oxygen concentrations. Due to the high porosity of the paper and ZnO, this sensor became attractive owing to its ease of fabrication and usage of very low-cost materials used in its construction, with high sensitivity even at low concentrations of oxygen in vacuum environments[6].

3. Temperature and Humidity Sensors

Several water cooling towers boiling water reactor and pressurized water reactor in nuclear power plants (NPPs) need humidity measurement at very high temperatures and very high humidity levels and sometimes in-situ measurements[7] at in situ conditions, e.g., core corrosive conditions, are desired to know the electrochemical corrosion potential (ECP). Temperature is one of the important parameters and is widely measured parameters in a NPP. No matter the type of plant, accurate and reliable temperature measurement is required for its operational distinction. Incorrect measurements can be because of electrical effects, nonlinearity or instability can result either in damage or loss of major equipment. Demands for high-temperature water chemistry sensors are increasing and research in those areas have accelerated for application in NPPs. Using advanced temperature instrumentation[8] that can solve problems of the plant's maintenance department, where it was located? and what to do about it? long before anyone in operations even suspects the existence of such an issue. A thermocouple is used for high temperatures of 3100°F. T/Cs which will answer faster to temperature changes than an RTD and these are more durable, allowing their usage in high vibration and shock related applications. Thermocouples[9] are selected according to the temperatures and conditions expected:

- For temp. < 1,000°F and locations subject to low-corrosion atmos.: NiCr-Ni (Type K)
- For temp. < 1,832°F and corrosive atmos.: NiCr-Ni (Type N)
- For temp. > 1,832°F: Pt Rh-Pt (Types R and S).

Understanding the process chemistry and coolant systems in nuclear reactors[10] is important and strongly controlled to minimise material degradation, also to regulate nuclear reactor’s power. Thus, pressurised water reactors mainly rely on boron additions to the primary coolant in order to control core reactivity throughout a fuel cycle but there is a need to balance the acidic concentrations with LiOH to minimise corrosion and transport of corrosion-products[11].

Many devices such as health monitors, oil-drills, and nuclear reactors need internal sensors to monitor physical states such as humidity, temperature. Novel photonic structures[12] measure temperature and humidity are tiny and highly accurate sensors[13]. Tiny photonic sensors made of silicon provide accurate readings without being damaged even in corrosive, toxic, and explosive conditions. Singapore, ASTAR’s researchers from IME developed a tiny optical temperature sensor (120x80 µm) (See Figure 1).  

Figure 1. Photograph of a tiny photonic-based dew point temperature sensor works by detecting changes in the refraction of light.

4. Fissile materials
Groundwater contamination is possible with radioactive wastes leakage that can pose a serious danger to the environment and mankind, example: U and Pu oxides and their derivatives are major elements present in groundwater and soils around contaminated sites and near production facilities. Henceforth trace monitoring of such fissile materials are essential in nuclear forensics. Owing to their properties, researchers studied Graphene and GO as novel sensing molecules for the detection of radionuclides such as U and Pu. Graphene can act as an effective sensor after functionalized[14] to for detection of fissile materials such as uranium and plutonium derivatives. Strong signatures of the sorption of uranium or plutonium moieties obtained due to the changes in the plasmonic properties of a finite graphene sheet, molecular electrostatic potentials, and current−voltage characteristics in oxidized graphene nano-junctions. By understanding the change in current due to the presence of U or Pu complexes near a Graphene and GO, we should be able to detect trace concentrations of these radionuclides.

5. MEMS/NEMS
MEMS and NEMS also play a significant role, if involved in the nuclear industry for sensing. Miniaturized gas chromatography (GC) systems are relatively fast in sensing gases, volatiles and also available in an ultra-small package. A new miniaturized microelectromechanical (MEMS) system which is a combination of accelerometer and gyroscope sensors for synchronized extraction of respiratory and cardiac signals, an application in nuclear medicine, aiding in cardiac, respiratory, and
patient body motion artefacts which can degrade the image quality and quantitative accuracy in nuclear medicine imaging leading to improper diagnosis, redundant treatment and scarce therapy.

Chemical sensor technology using nano electromechanical systems (NEMS) mass detectors took detection to the next level comparatively with its high speeds of detection, specificity, sensitivity, and volume required than their MEMS counterparts. NEMS sensors have demonstrated successfully the detection of sub-parts per billion (sub-ppb) concentrations by combining two channels of NEMS detection with an ultrafast front-end GC, chromatographic analysis of 13 chemicals was completed within a window of 5 sec. NEMS sensors detected DIMP (diisopropyl methyl phosphonate) in subparts per billion[15] (ppb) concentrations.

6. Conclusion
Sensors play a key role and required for condition monitoring, measurement and control, predictive maintenance, and accidents in every industry. The key to achieving to the modern day needs to develop an integrated tactic for monitoring, control, fault detection and diagnosis of plant components such as sensors, actuators, control devices and other equipment. Nanotechnology and nanoscale materials are a new and exciting field of research and nanosensors have probable usefulness in a diverse range of applications and noteworthy advantages over macro-scale sensors. Nanosensors are not just small sensors, but rather sensors that utilize/detect nanoscale phenomena. A selective range of sensors/nanosensors has been surveyed, categorized and discussed according to their working mechanism, which was then compared to their applications, especially for the nuclear industry.

Wireless sensors are very useful in industrial processes towards measurement and control, condition monitoring, predictive maintenance, and accidents. Wireless sensors/networks are very prevalent and required in large scale in any industry. Wireless technology offers numerous opportunities in power generation, ranging from data, sensor networking, simplifying the communication between sensors and voice communications to equipment condition monitoring. Use of WSNs for condition monitoring is an emerging field with many manufacturers providing choices for the industry looking to grow or enhance existing maintenance programs.

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