iDREAM: an industrial detector for nuclear reactor monitoring

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Abstract. Prototype of industrial reactor antineutrino detector iDREAM is dedicated for an experiment to demonstrate the possibility of remote monitoring of PWR reactor operational modes by neutrino method in real-time in order to avoid undeclared exposure modes for nuclear fuel and unauthorized removal of isotopes. The prototype detector was started up in 2014. To test the detector elements and components of electronics distilled water has been used as a target, which enables the use of Cerenkov radiation from cosmic muons as a physical signal. Also parallel measuring of the long-term stability has been doing for samples of liquid organic scintillator doped with gadolinium and synthesized by different methods.

1. Introduction

Nuclear power belongs to the list of Priority Development Areas in Science, Technology and Engineering in the Russian Federation approved by Russian Government. It is also the fact that Russia is one of few worldwide player on the nuclear power plant world market including Nuclear Power Plant (NPP) R&D&Construction together with complete NPP fuel cycle. In February 2010 the federal target program aimed to bring a new technology platform for the nuclear power industry based on fast reactors have been approved. Rosatom's long-term strategy up to 2050 involves moving to inherently safe nuclear plants using fast reactors with a closed fuel cycle. It is expected that NPP will provide 45-50 % of electricity at that time.

It is important to notice that the development of the neutrino detector for diagnostics of a reactor active zone is one of the announced aims included in to the Federal program "Development the nuclear power complex" within the Federal Targeted Program "The nuclear technologies of the new generation for the time period from 2010 to 2015 and for the period until 2020".

The neutrino method for monitoring the operating modes of nuclear reactors was proposed and tested in the 1980s–1990s at the Kurchatov Institute and it was confirmed experimentally at Rovno NPP[1]. This method is based on the registration and interpretation of inverse beta decay (IBD) products with liquid organic scintillator optimized for neutron capture.

Until recently the detectors of reactor antineutrinos have been designed mainly for research purposes. By the way, a collaboration of Russian institutions (the Skobeltsyn Institute of Nuclear Physics, the Kurchatov Institute, the Institute for Nuclear Research, and the All-Russia Research Institute of Automatics) set as their goal to construct a test prototype of the iDREAM (industrial Detector for REactor Antineutrino Monitoring).

2. Project goal

The original application of iDREAM was to demonstrate industrial version of neutrino method and extend the efficiency of nonproliferation procedures for operating NPP being additional "black-box"-like unattended instrument with secure communication links directly to IAAE. By the way this detector have much wider application areas including research and education. Compact size, low cost and expected high detection efficiency makes the detector a unique research instrument to study perspective NPP reactors including future perspective VVER and fast-neutron reactors. The iDREAM application purpose is to provide a reliable information about active zone condition by measuring antineutrino flux from NPP reactor which cannot be falsified.

3. Monitoring methods

The IBD reaction which is used to detect antineutrinos produces a positron, whose energy depends on the initial antineutrino energy, and a neutron:

$$\bar{\nu}_e + p \rightarrow n + e^+$$

Since the threshold of this reaction is 1.8 MeV, only 25% of the total number of antineutrinos emitted by the reactor (the ones with their energy above the threshold) are detected. The most appropriate target materials are hydrogensaturated transparent plastic or liquid organic scintillators (LOSs). The IBD detection method was originally proposed by Frederick Reines in mid 1950's [2]. The method is based on the detection of two consecutive scintillation flashes (photons of luminescence): the first pulse is due to a positron (the ionization of the medium with subsequent annihilation) while the second pulse is due to neutron capture within the target with the immediate irradiation of gamma which energy and number depends on the capture nuclei. Clear time stamp allows to suppress the background considerably using the delayed coincidence technique.

The number of the detected IBD events is proportional to current power of reactor and directly corresponds generated energy. The calculations and the results of experiments that were conducted earlier show that the detector count rate is about 10^3 events/day at a distance of 10-20 m from the core of a nuclear reactor with an output of, for example, 1.4 GW if the sensitive LOS volume is about 1 m^3 and the efficiency of detection of the IBD products is 60%.

4. Detector construction

The detector (Figure 1) design incorporates two concentric stainless-steel tanks with a common sealed cap. The inner tank is divided by a convex transparent organic glass membrane and is scanned by 16 PMTs. The inner tank volume (1 m^3) below the membrane is filled with a LOS doped with gadolinium and serves as the detector target. The target may be accessed via a vertical pipe that is glued into the membrane center. The upper end of this pipe is outside of the tank. The inner tank volume above the membrane is filled with linear alkylbenzene (LAB), which helps to increase the light collection efficiency and shield the target from the gamma background from PMTs. The outer tank is also divided vertically into two parts for transportation and handling convenience. The circular volume is filled with scintillator liquid and serves as an active shield for the detector target. It also helps to increase the overall efficiency by detecting the gamma quanta that escape the target volume. The circular volume is scanned wby 12 PMTs. A light-protective barrier between the buffer and the circular volumes is located at the bottom side of the cap. The LOS is pumped in and out in the target and in the circular volume via a header using a system of pipes and circular separators at the bottom of the inner and the circular volumes. In order to increase the light collection efficiency, the inner walls of the buffer and the main sensitive volumes are covered with a reflective material (Lumirror E6SR) with a reflection coefficient of up to 90% within the scintillation spectrum of the LOS. Thus, two liquid scintillator types (with and without gadolinium) and a buffer liquid are used in the detector. The total volume of these liquids, which are based on LAB, is roughly 3500 L. Original DAQ system based on industrial 1Gsample/s flash analogue to digital converters (FADCs) is used to process PMT outputs. Use of FADCs allows to introduce in to data analyses pulse shape discrimination technique. Set of summing-discriminating modules of fast electronics together with original flexible programmable trigger based on FPGA have been developed for DAQ system of iDREAM to reduce data stream of raw data. Slow control system based on industrial CAN-bus/CANopen network with a set of industrial sensors and originally developed electronic instruments was developed to control high voltage power supplies, DAQ thresholds, LOS levels and ambient conditions.

5. Developing a liquid organic scintillator

The lack of a stable, inexpensive, nonflammable, and nontoxic LOS was one of the problems that hinder the development of industrial detectors for nuclear reactor monitoring. The LOS instability, which was manifested in the deterioration of its characteristics (light output and transparency), limited the lifetime of such detectors as the RONS and CHOOZ detectors.
The primary requirement for a small–volume ($\sim 1\text{m}^3$) industrial detector consists in maintaining a stable light output and a stable neutron detection efficiency (i.e., preserving a constant concentration of gadolinium for a protracted period of time), while the scintillator transparency is not a crucial parameter, although it may reflect the degree of chemical purity of the LOS components. An original liquid scintillator based on Russian LAB (TU 2414–028–05766480–2006) was developed for the iDREAM instrument. A concentrate containing a base gadolinium substance with a gadolinium concentration that is ten times higher than its resulting concentration in the LOS was proposed for use in order to introduce gadolinium into the LOS. The concentrate with gadolinium was dissolved in the scintillator with the fluor (PPO, 3 g/L) and the shifter (POPOP, 0.03 g/L), which was prepared beforehand [3].

6. Conclusion

To the present time it was developed and adjusted the detector construction, some of modifications are in progress. During the first physical start of the detector with a distilled water all systems were tested and showed an operational suitability. Three LOS samples of scintillator with three different gadolinium compounds are testing for stability.

For the near future it is planning to shift the detector to the underground laboratory specially developed in SINP MSU to study efficiency and background suppression capabilities of the detector. The second long term activity is focused on continuous study of LOS samples stability in order to select the sample for the whole detector. The following step involves the installation of the iDREAM at NPP for final test during reactor campaign. The negotiations about such testing are in progress.

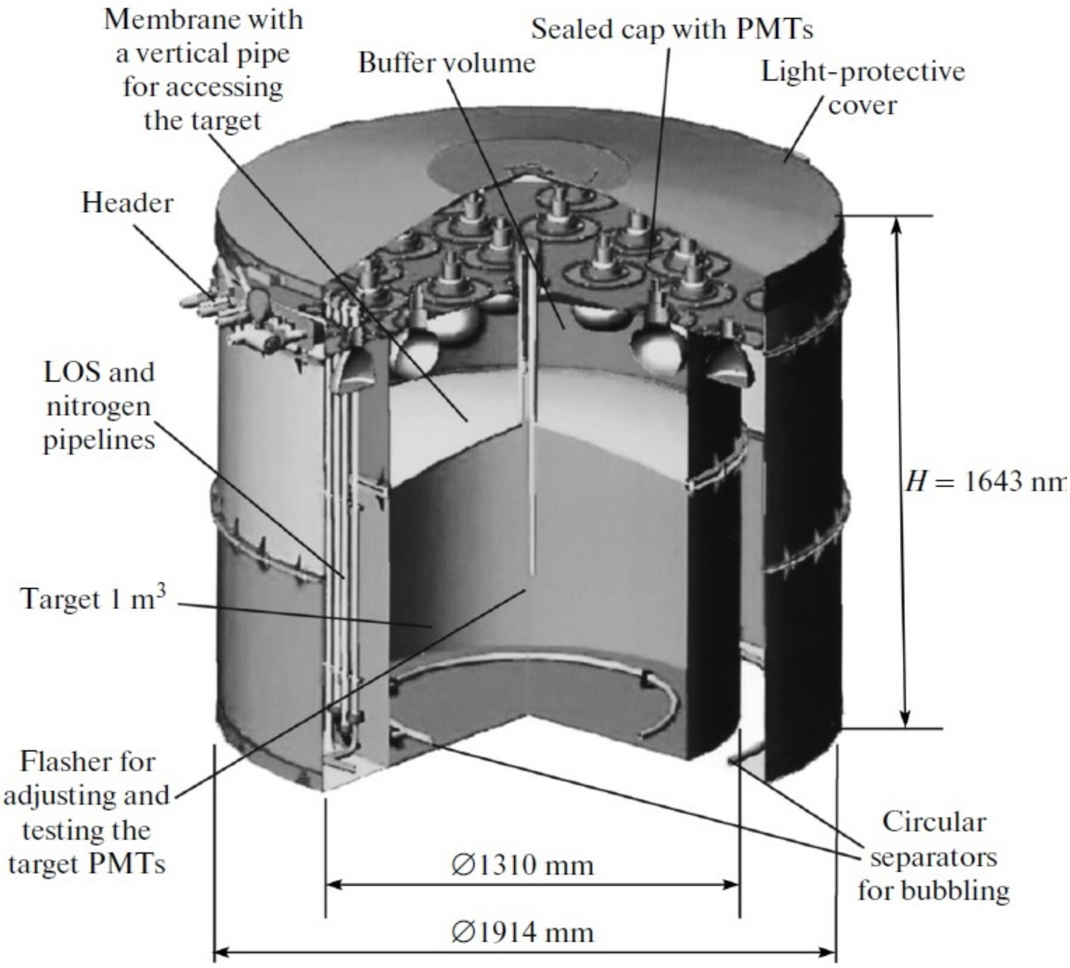

Figure 1. iDREAM Construction

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References
[1] Borovoi A and Mikaelyan L 1978 (in Russian) *At. Energy* **44** 508 (original Russian title: *Atomnaya Energiya*)
Klimov Yu V *et al.* 1990 (in Russian) *Nucl.Phys* **52** 1579 (original Russian title: *Yadernaya Fizika*)
Kopeikin V I, Mikaelyan L A and Sinev V V 1997 *Phys. At. Nucl.* **60** 172
[2] Reines F 1979 *Science* **203** (4375) 11
[3] Novikova G Ya, Bakulina N I and Morgalyuk V P 2014 *Russ. J. Inorg. Chem.* **59** 244
Bakulina N I *et al.* 2014 *Preprint* 1387/2014 (Moscow: Institute for Nuclear Research Press)