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DETECTOR FOR SAFEGUARDS MEASUREMENTS

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High Sensitivity, Low Profile Neutron Detector for Safeguards Measurements

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Abstract

A neutron detector has been constructed and tested at Pacific Northwest Laboratory (PNL) for the purpose of making fast, high sensitivity measurements of neutron emitters in portal applications. The system is based upon glass fiber optic scintillators loaded with lithium-6 and operated to detect thermal neutrons. Due to their compact size, physical flexibility, freedom from microphonic pickup, and complete lack of environmental and safety concerns, these fibers are very suitable for some applications. The electronics needed for these fibers is somewhat more complex than for helium-3 proportional counters, but the entire electronics package (including the controlling computer) has been shrunk into a space of 20 x 25 x 2 cm. The prototype sensor is about 180 x 60 x 7 cm, but a final design now under construction measures 200 x 28 x 2.54 cm. The new, smaller detectors will be capable of ganging to achieve any needed sensitivity and will each weigh about 16 kg. The principles of operation of the fiber will be discussed as will the operational mode of the detector.

I. INTRODUCTION

Portal applications include entrances and exits of US nuclear facilities. In facilities that handle neutron emitting materials, particularly plutonium, a great deal of care is understandably taken to control the movement of machinery, materials, and people to prevent the accidental loss or deliberate diversion of nuclear material. The consequences of both forms of release are potentially grave. For either case, the emplacement of an alarmed detector on a loading dock, for instance, would improve confidence in the measures taken to prevent loss.

A detector of this sort should be of sufficiently low profile that it does not obstruct the portal it is designed to protect. To this end, our detector has been constructed to allow foot traffic or hand trucks directly across it, and it is sized to fit between the left and right wheels of a passing vehicle.

In addition to permanent emplacements, this sensor could be used to make spot checks at a portal, and has thus been engineered to be portable by one operator and to run on a car battery. A graphical user interface is being developed on a palm-top computer to allow field set up, field diagnostics, and documentation of positive measurements.

Finally, options have been explored to allow the sensor to be operated remotely and to transmit measurement data periodically by commercial satellite.

II. FIBER PROPERTIES

The central physics of this sensor is the very large thermal neutron cross section of lithium-6 and the very large scintillation signal produced by the disintegration of lithium-7. When an alpha and a triton are released with 4.8 MeV in a scintillator, a large number of scintillation photons are produced. When this occurs in a fiber optic, only those photons emitted within a small cone may remain in the fiber; others simply escape the fiber to be absorbed in some cladding material. Those within the acceptance cone, called the numerical aperture, will be reflected at the interface of the fiber and its cladding, which has a lower index of refraction.

The short range of alphas and tritons in glass also means that the entire signal can occur in a very small volume. A glass diameter of 120 microns was chosen to keep a large portion of the absorption events within a single fiber. A diagram of a typical event is provided in Fig. 1.

Fig. 1 Example of a thermal neutron event

Eventually, some of the photons produced by a neutron absorption may survive the trip to one of two phototubes instrumenting the fiber. The number of survivors, usually low, must then be converted by the photo-cathode of the tube into electrons for the tube to amplify. This conversion, governed by the quantum efficiency of the photocathode, usually reduces the number of survivors by about eighty percent. These photo-electrons are governed by Poisson

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statistics, which significantly reduces the energy resolution of the device. The signal from a neutron is nevertheless above tube noise. Tube noise is effectively canceled by coincidence requirements, as discussed below.

Gamma ray sensitivity could be a concern in a scintillator, and a great deal of Monte Carlo calculations have been carried out, as well as empirical measurements, to understand and control this sensitivity. A fission spectrum of gamma rays was used to approximate an average gamma ray in calculations. Given an average gamma ray energy of 0.5 MeV, the secondary electrons ejected from a gamma ray interaction traveled, on average, four fiber thicknesses in the forward direction before being stopped, depositing some energy in each traversed fiber. A detector geometry and matching electronic circuit were designed to use these properties to allow classification of a signal as a neutron or gamma ray. This mainly operates in the region of the glass where many fibers are gathered into a bundle to mate to a phototube.

A critical limiting factor in the production of detectors from lithium loaded glass fibers is the attenuation length of light in the fiber. Though work by others [1] has been done in this field, PNL-produced fibers regularly exceed one meter in the half-length ($D_{1/2}$) of light. In fact, fibers with $D_{1/2} = 2\text{m}$ have been made.

It is important to have long lengths to establish a good ratio of neutron sensitivity to gamma sensitivity, since the neutron sensitivity is proportional to the mass of the glass and the gamma sensitivity is basically proportional to the mass of glass in bundles only. The cost of electronics is essentially proportional to the number of phototubes, so longer fibers translate into a cheaper system if the mass of glass is fixed. At two meters half-length, a system with several square meters of glass is reasonably similar in cost to an equal area covered with helium-3 tubes.

III. DETECTOR CONSTRUCTION

The fibers are drawn with a 120 micron diameter in a dedicated facility at PNL and are typically fabricated into sheets 1 x 2 meters in size. For this application, the flat fiber panels were fabricated at 26 x 180 cm and two fibers thick. Each thin fiber panel was independently coated with an exceedingly thin coating for surface protection and light-tightness. Three such panels were overlaid at a final thickness of less than 3 mm. This assembly, now composed of six monolayers in three pairs, was sheathed in a hydrogenous material for mechanical protection and some neutron thermalization, nearly filling the light-tight enclosure.

The fibers are instrumented with small phototubes in a matrix arrangement, shown in Fig. 2, and connected to a special nucleonics circuit for gamma/neutron selectivity, as described below. The circuitry produces counts, which are scaled by a special computer system that is described below. The prototype used for testing is shown in Fig. 3. The next generation sensor is about half as wide, half as thick, and

incorporates a miniaturized electronics package in the sensor housing.

IV. SIGNAL PROCESSING

Since the glass fiber is slightly sensitive to gamma rays, electronic signal processing is done to separate gamma ray signals from neutron signals. This is achieved by segregating events into two groups based on several properties the signals may possess. The segregation is centered on the fact that a neutron signal is large and concentrated in one fiber, while the gamma signals are either vanishingly small, or deposited among several adjacent fibers.

Fig. 2 Two bundles in gamma ray identification matrix

To capitalize on these basic properties, the flat groups of fibers are gathered into a matrix of bundles. This matrix provides a crude position sensitivity, which when coupled to energy discrimination, allows gamma/neutron selectivity.

For instance, to be classified as a neutron event, a signal should have a large total energy, but should also be registered in two (and only two) phototubes that are connected at opposite ends of one portion of the sensor. Further, each of the two phototube signals should be above a threshold. This additional constraint prevents bundle-detected gamma rays from passing as neutrons. In this somewhat simplified view, a signal possessing these qualities would produce one count in the neutron channel.

The gamma channel is not simply the total signal minus the neutron channel. Phototube noise is eliminated by requiring a coincidence for any detection and enforcing a minimum total signal strength. Thus temperature effects, microphonics, and many types of noise are immediately removed.

V. DATA HANDLING AND USER INTERFACE

The special circuit described above is connected to an embedded PC/104 system that continuously monitors system performance and can autonomously make background measurements and set an alarm condition, without user intervention.

The system is eventually expected to operate without a dedicated user, so the embedded processor continuously measures background and can set an alarm condition when a

selected threshold is crossed. The threshold is set by the user to reflect the needed sensitivity and the acceptable false-positive alarm rate.

A user interface is currently provided through a serial cable optionally connected to the outside of the sensor box. Any terminal may be used to set up the sensor, but palm-top computers are favored by the developers. The currently operational mode of the software allows a complete periodical data dump to be viewed on the screen and saved to disk file. In fact, all testing has been done in this way.

An enhanced user interface is being written for a palm-top PC at this time to provide a real-time graphical representation of the neutron and gamma signals for diagnostics and set-up. This interface will also automatically provide a log of all events exceeding the user-defined threshold.

Fig. 3 Prototype in field deployment mode

Inmarsat-C options have been explored to give low cost real-time remote operation. Simply put, the computer need only periodically compress and send data to a shoe-box sized transmitter equipped with an omni-directional antenna to accomplish this objective. A large number of detectors could be deployed in this way to give a central computer complete control of portals in a vast facility.

A final operational mode is being developed to allow several detector boxes to be strung together to tailor the sensitivity of the system to user-specific needs. This will be field-implemented, such that the system can be customized by the user to best suit local needs.

VI. TESTING AND RESULTS

Testing of the prototype confirmed that small quantities of neutron emitter could be measured in a short time, which is no surprise, and that the electronic/PC system is robust enough to run for long periods with no mishap. The prototype has been in essentially continuous operation for nine months in several locations. Realistic outdoor testing on a vehicle was

successfully completed and the prototype has been operated over a wide temperature range.

Neutron moderation has been provided by external polyethylene slabs in laboratory testing. However, outdoor tests relied only on moderator available in asphalt paved surfaces, thereby eliminating the need for moderator outside the detector housing. This should make the detector much more attractive to those interested in rapid deployment.

In conclusion, a novel sensor material has been applied to a need in the safeguards/non-proliferation community. Though several of the sensor material's performance characteristics could be found to be in common with helium-3 tubes, in the area of microphonics the novel fiber optic material may be superior. In addition, no transportation or shipping restrictions exist for the fiber optic sensor. Certain difficulties do, in fact, arise from the use of compressed gas tubes, such as helium-3. Extremely serious restrictions apply to the transportation of pressurized tubes which contain hazardous compressed gasses such as barium fluoride (BF₃).

The elimination of these environmental concerns and the development of a powerful, flexible electronics package signify that, at least for certain applications, there may be a future beyond helium-3 in thermal neutron measurement.

VII. REFERENCES

- [1] G.B. Spector, T.McCollum, "Advances in lithium-loaded glass scintillator fiber development," NIM, Vol. A313, pp. 373-376, 1992.

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