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NUCLEAR-OPTICAL CONVERTERS FOR NEUTRON DETECTION

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ABSTRACT

Nuclear-optical converters (NOC) are fission chambers based upon fission fragment energy conversion to optical radiation in gas luminescent media. The All-Russia Scientific Research Institute of Experimental Physics (VNIIEF) has demonstrated that it is possible to construct nuclear-optical converters with characteristics appropriate for a wide-range of measuring applications including neutron detection in nuclear power plants. These detectors may be used a number of different modes: pulse count, luminescent (equivalent to current mode in ionization detectors), and lasing (essentially a neutron switch).

NOCs offer a number of potential advantages over ionization detectors. The detectors require no power supply. Signals are transmitted via light-pipe or fiber optics rather than insulated electrical cable. The detectors are less sensitive to gamma radiation. NOC can produce large signals, obviating the need for pre-amplifiers near the detector. It is possible to construct a single detector which measures flux at many discrete points and at the same time provides total flux along a line containing these discrete points.

This paper describes the construction and testing of NOC at VNIIEF; the range of characteristics thought to be reasonably attainable with nuclear-optical converters, and possible applications to nuclear power plant instrumentation.

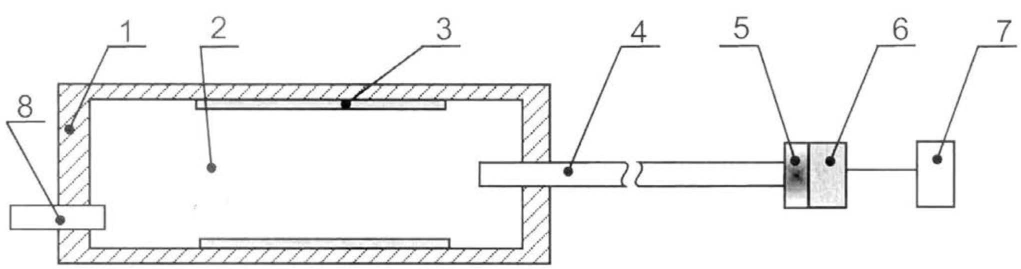
1. INTRODUCTION

Research concerning the possibility of building neutron detectors based upon nuclear-optical converters was carried out by VNIIEF under contract to Lawrence Livermore National Laboratory (LLNL) as part of the US Department of Energy's Initiatives for Proliferation Prevention [1]. In VNIIEF during about thirty years, investigations of spectral-luminescent characteristics for various gas media excited by nuclear radiations were carried out in the framework of program on nuclear-pumped lasers [2]. The initial work studied the luminescent characteristics of rare gases and its mixtures under excitation by uranium fission fragments. This work led to the conclusion that nuclear-optical converters could be built in which the light power output is a linear function of neutron flux over a range of 10^8 to 10^{16} n/cm^2-sec and that can operate in a pulse mode below that range. In addition, previous work showed that neutron pumped lasers of similar design may be built to laze at selected fluxes above 10^{12} n/cm^2-sec.

2. DETECTOR CHARACTERISTICS

2.1 Physical Construction

The nuclear-optical neutron detector developed by VNIIEF is a gas-tight metal or quartz capsule, lined with a ^{235}U layer on the inner surface, and filled with a radioluminescent gas mixture. Upon exposure to neutrons, fission fragments from the ^{235}U layer excite atoms of the gas mixture and relaxation of the excited atoms produce a light signal. The light signal may be withdrawn using an optical fiber or a light pipe and sent to a photodetector for conversion to an electrical signal which in turn may then be processed by conventional electronics. Figure 1 shows the construction of a neutron detector based upon a nuclear-optical converter. The detector may be of almost any size from a few cubic millimeters to many cubic centimeters with the sensitivity and total power output dependent upon size and gas pressure.



1 - detector body; 2 – gas medium; 3 - fission fragment source; 4 - fiber; 5 - filter;

6 - photodetector; 7 - wide-range system of neutron flux measuring; 8 – fill nipple.

Fig. 1 Principal Schematic of the Nuclear-Optical Neutron Detector

2.2 Performance Characteristics

Study of various possible gas media and testing of an experimental detector showed that the sensitivity of such a device can be on the order of 10^{-17} W per 1 neutron /cm^2-s. The experimental device exhibited a useful linear response over the range of 10^8 to 10^{16} n/cm^2-s. Sensitivity to gamma radiation is approximately 1/10,000 of the detector’s sensitivity to neutrons.

The device can operate also in a pulse mode from about 10 to 10^8 n/cm^2-s. Signal losses in the optical fiber, however, restrict the use of this mode to situations in which the photodetector can be located close to the detector.

By adding a mirror on each end of the capsule the detector can also operate in a lasing mode as nuclear-pumped laser [2]. In the lasing mode the detector is a threshold device. The minimal threshold of nuclear-pumped lasers has been found to be approximately 2×10^{12} n/cm^2-s [2]. Above that level the laser power output is a linear function of input neutron flux density.

2.3 Environmental Characteristics

Since the detector is made entirely of glass or metal, gas, and uranium the detector is environmentally very robust. The environmentally limiting component is the optical fiber. Radiation induced darkening of fiber limits the use of the system to total doses up to 10^7 Gy. Above these levels a light pipe, rather than optical fiber may be used to remove the light signal to an area of lower radiation exposure.

The lifetime of the NOC based detector has not been tested. The life of the detector is limited by depletion of the ^{235}U. Analysis of this mechanism predicts that such a detector will function at least to a burnup of 10^{21} n/cm^2.

2.3 Advantages

When compared to conventional ionization based fission chambers NOC based devices offer a number of potential advantages.

- The detector requires no power.
- The detector produces a large power output; the output power can easily be in Watts or tens of Watts in the current mode.
- High time-resolution (~ 1 ns) in the case of registration of pulse neutron fluxes.
- Wide choice of gas media radiating from UV to IR spectral ranges that allow adjustment of the NOC output spectrum to match the transparency spectrum of transmission media (e.g., optical fiber) and spectral sensitivity of photodetector.
- The detector system has a very low sensitivity to gamma radiation. The NOC sensitivity to gamma radiation is about five thousand times less than that of a traditional fission counter. Furthermore, fiber-optic cables and light pipes are much less susceptible to gamma induced noise than are coaxial cables.
- Sensitive electronic components can be located at a great distance from the detector in a controlled environment.
- Optical signals offer the opportunity for splitting the light signal into multiple channels without jeopardizing electrical independence.
- A test or calibration source can be readily connected to the signal transmission channel, again without jeopardizing electrical independence.
- The detector offers the possibility of building instrumentation or control functions which rely only upon the light output. Such devices would be powered only by the energy generated by the detector.

3. TESTING

VNIIEF has a unique collection of pulse nuclear reactors [3]. These are used as powerful sources of penetration radiation in technical, radiochemical, and biophysical investigations. Two of these reactors, the VIR-2M and GIR2 were used to investigate the performance of NOC used as neutron detectors. These reactors operate with pulse half-with of 3 ms and 300 μs, respectively.

Testing was conducted in pulse, quasi-pulse, and continuous reactor modes. Some results of NOC testing in the case of VIR-2M reactor are shown in Figures 2, 3, and 4. As neutron source we used the usual fission chamber [4]. Measurements showed that above 10^8 n/cm^2-s the detector response was a linear function of neutron flux up to at least 10^{16} n/cm^2-s.

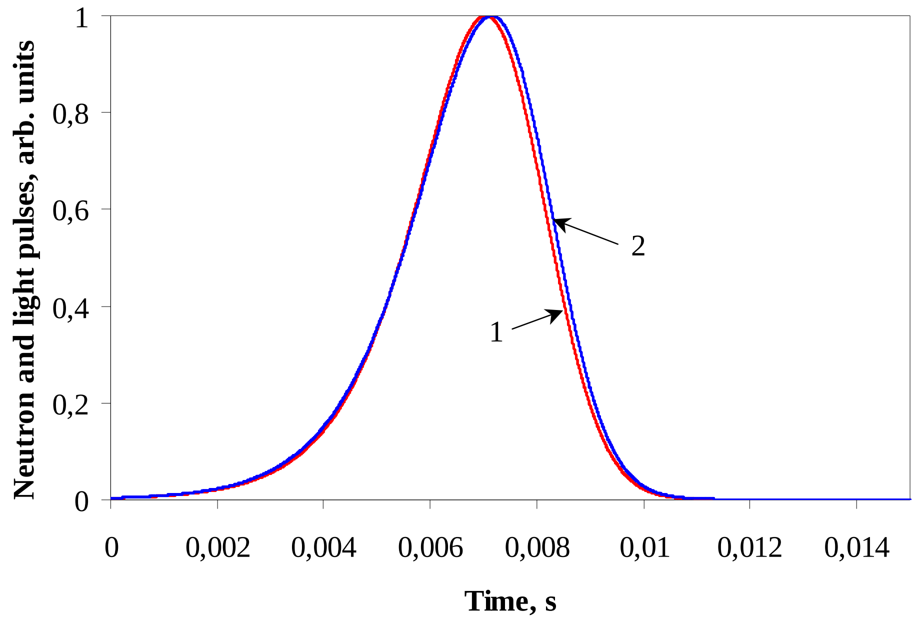


Fig.2 Neutron (1, red line) and light (2, blue line) pulses for the Ne-Kr (1.7 % Kr) mixture at 0.64 atm pressure (VIR-2M reactor, energy release in reactor core is 55.2 MJ).

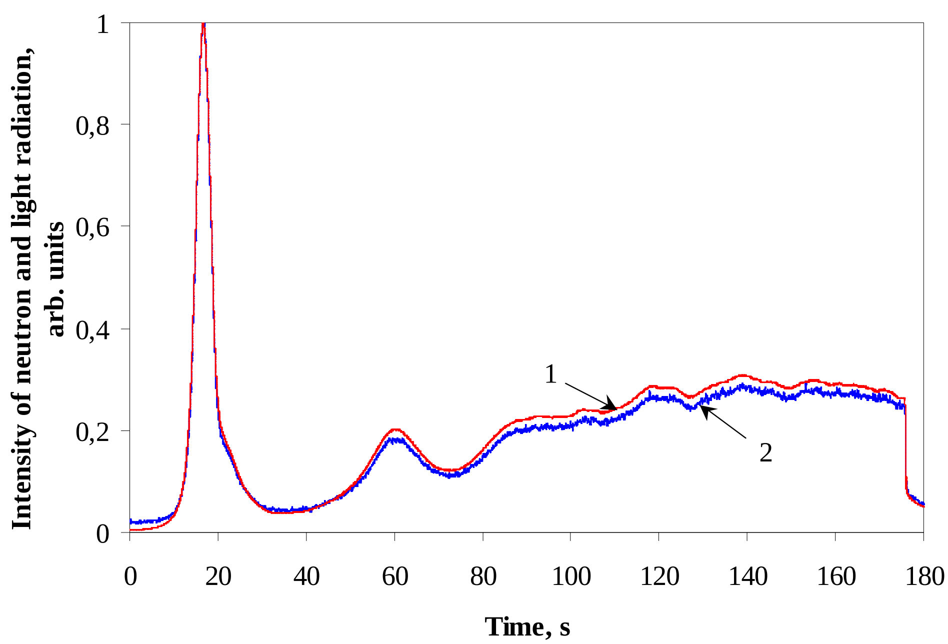


Fig.3 Time dependence of neutron (1, red line) and light (2, blue line) intensity for the Ne-Kr (1.7 % Kr) mixture at 0.64 atm pressure. VIR-2M reactor operates in “quasi-pulse” mode (peak power is about 1 MW).

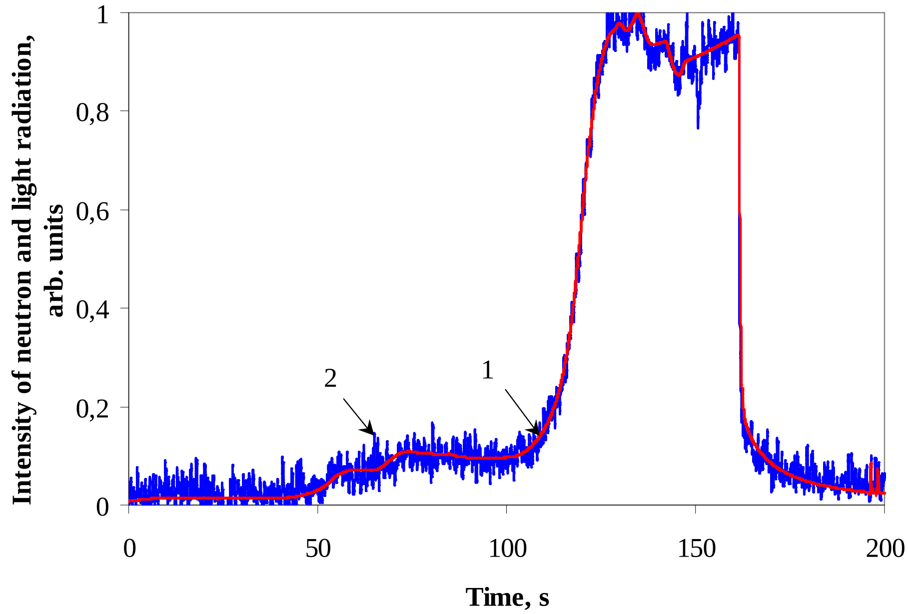


Fig.4 Time dependence of neutron (1, red line) and light (2, blue line) intensity for the Ne-Kr (1.7 % Kr) mixture at 0.64 atm pressure. VIR-2M reactor operates in continuous mode (maximum power is about 1 kW).

4. POSSIBLE APPLICATIONS

The nuclear-optical detector has the potential to replace electronic detectors in many existing applications. For example, detectors of appropriate size could be developed to replace in-core detectors for VVER reactors.

The detector design also offers the possibility of developing novel detector or detector system concepts. For example, as illustrated in Figure 5 it would be possible to build a single long detector in which measured both total average flux over the entire length of the detector and local axial flux at individual points along the detector. The light signal representing the average total flux is extracted by a fiber positioned at the end of the detector to view all of the light generated, while the local flux signals are extracted by individual fibers positioned to view only a the portion of the light emission stimulated near a single location.

Another example is an emergency shutdown system designed and tested for the BIR-2M pulse reactor [5]. In this system, shown in Figure 6, a polyethylene shutdown rod (bullet) is driven into the core by a very small (1g) explosive charge. The explosive charge is detonated by the light output from a nuclear-optical converter when it crosses the threshold into the lasing mode. The construction of the detector is tuned to lase when the emergency actuation threshold is reached. This system is totally independent of electrical power.

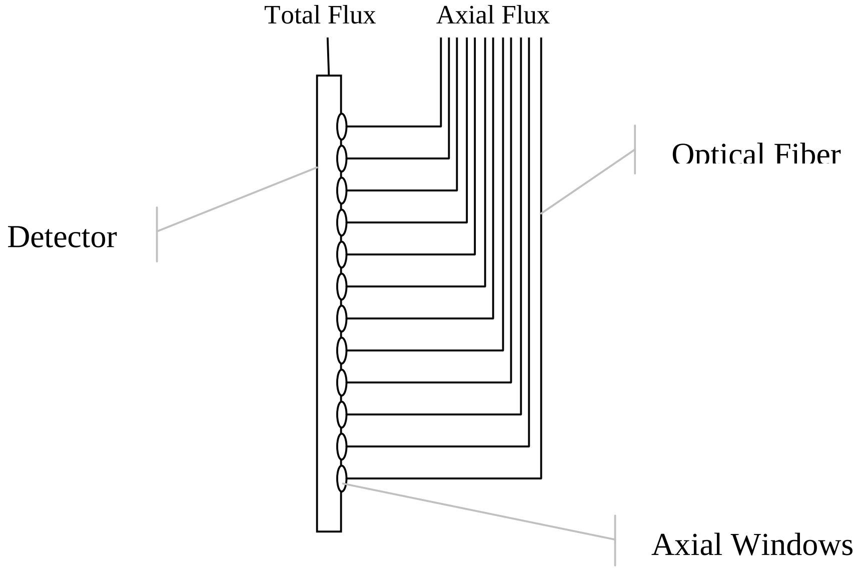
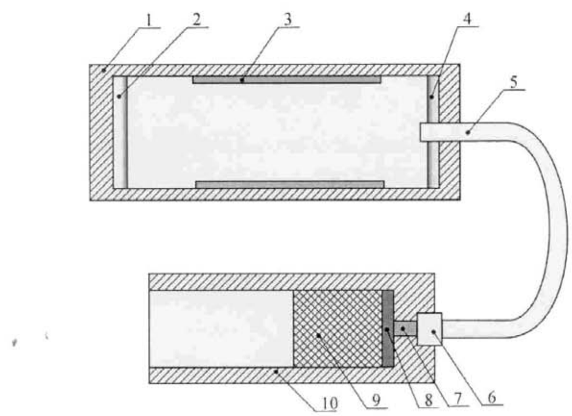


Fig. 5 Conceptual axial and total flux detector



1 - detector body, 2, 4 - resonator mirrors, 3 - source of fission fragments, 5 - fiber,

6 - light detonator, 7 - transmission charge, 8 - throwing charge, 9 - polyethylene bullet,

10 - barrel.

Fig. 6 Example of passive emergency shutdown system

5. CONCLUSIONS

The possibility of construction neutron detectors based upon the principle of nuclear-optical converters has been demonstrated. Such detectors may be suitable replacements for existing neutron detectors and offer significant advantages in performance and environmental robustness. Such detectors also offer the opportunity to build new kinds of instrumentation and control systems that are not possible using traditional ionization based detectors. The main problems still to be overcome involve developing fiber optics or other mechanisms which can for transmitting the light signal from a high radiation environment without sustaining rapid environmental damage and in determining the actual lifetime of detectors under application conditions.

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