Title: MICRO CAVITY FISSION CHAMBER RADIATION DETECTION SYSTEM

Abstract: A radiation detector for use to monitor the neutron flux of a nuclear reactor, is provided. A small dielectric substrate that has a low neutron-activation cross section is provided and is coated with a neutron conversion material, such as uranium oxide or thorium oxide. A micro-sized detection cavity, or micro-pocket, in the substrate is filled with a detection gas, such as argon. A voltage is provided across the anode and a cathode in the detection cavity. As a neutron enters in to the detector system, it may be absorbed in the conversion material. The small size of the detector volume minimizes energy deposition into the detection gas by gamma rays, fast electrons and beta particles, and therefore minimizes false counts.

FIG. 4

before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))

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MICRO CAVITY FISSION CHAMBER RADIATION DETECTION SYSTEM

CROSS REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of U.S. provisional patent application No. 62/203,817, filed August 11, 2015.

STATEMENT OF GOVERNMENT RIGHTS

[0002] The invention was partially funded by the U.S. Government under the Department of Energy Grant Nos. DE-AC07-05ID14517 and DE-NE008305. Accordingly, the US Government may reserve certain rights to its use.

TECHNICAL FIELD OF THE INVENTION

[0003] This invention relates particularly to a new type of miniaturized neutron detector that is inherently insensitive to gamma-ray radiation and can withstand the high-heat and high-radiation environments such as those found inside an operating nuclear reactor environment, including the nuclear reactor core.

Background of Invention

1. Field of Invention

[0004] This invention relates to neutron detectors, methods of making the same, and in particular, to miniaturized fission neutron detectors for use in a high neutron flux environment and methods of making the same.

2. Background Art

References Referred to Herein


The need to monitor the neutron flux (i.e. neutrons per square centimeter per second, \(n \text{ cm}^{-2} \text{s}^{-1}\)) within the core of a nuclear reactor has driven much research in varying methods of detecting said neutron flux. The neutron flux within the core of a nuclear reactor is indicative of its operational power level; where it is found that an increase in the neutron flux indicates an increase in the operational power level. In order to gain a complete understanding of the operation of a nuclear reactor, the neutron flux and power level must be accurately reported to operators. The high-radiation and high-heat environment found within a nuclear reactor core are not conducive to the operation of many types of radiation detectors. First, the high neutron flux found within a reactor core, often on the order of \(10^{14} \text{ n cm}^{-2} \text{s}^{-1}\), with very high gamma-ray fluxes (10\(^8\) R/h), will either burn up a detector's neutron conversion material too quickly, reducing the device's overall lifetime, or will induce a count rate so high that the detector becomes unreliable. Second, the high-heat present within most reactor cores, often exceeding 300°C, would either destroy many detectors systems (such as scintillators) or render them entirely unusable (such as would be the case for most semiconductors). Currently, solutions exist to monitor the neutron flux externally via radiation monitors that are kept well outside of the core. However, measurements can be skewed due to scattering and/or buildup within the materials found between the core and the detector system. Furthermore, information regarding minute variations in flux around the core, due to fuel burn up or control-rod insertion etc. is entirely lost at distances outside of the reactor core.

Development and deployment of small, accurate, and robust neutron flux measurement systems is an important enhancement for advancing nuclear fuel technology. A need exists for both nuclear test reactors, and commercial power reactors, to place neutron sensors within the reactor core to provide information on the neutron flux [1]. Furthermore, in-core sensors may typically be located within narrow channels within the reactor core (< 10 cm in
diameter) [1]. The physical requirements for in-core neutron sensors limit material selection and
device geometry. Several technologies exist which are used to measure neutron flux for in-core
and near-core environments.

[0008] Ionization chambers and fission chambers are commonly used for near-core neutron measurements [1]. Typical ionization and fission chambers are necessarily large, and are only capable of monitoring neutrons which have escaped the reactor core. Such devices are impractical for in-core measurements because of their large size, fragile construction, and large flux perturbation. Miniature fission chambers are commonly used for in-core neutron measurements. Miniature fission chambers are typically lined with highly enriched uranium, and are typically made in a cylindrical geometry [1]. Device dimensions for miniature fission chambers are usually in the mm to cm range. The burnup of fissile material and buildup of fission fragments in sealed miniature fission chambers greatly limits the application of such devices for extended periods of time. A fission chamber using enriched \(^{235}\)U will decrease in sensitivity by 10% after an integrated neutron fluence of \(10^{20}\) n cm\(^{-2}\) s\(^{-1}\) in a typical power nuclear reactor [2]. In order to extend stable device lifetime, fertile isotopes can be added to the neutron-sensitive coating [2]. The buildup of fission fragments in the sealed gas chamber of typical miniature fission chambers also produces a 'memory effect', where the radioactive decay of fission fragments in the detection gas produces a residual current, reducing device accuracy [1].

[0009] Alternatively, iron or gold activation analysis can be used to determine the neutron fluence within a reactor core during an operational period. However the neutron fluence is not as useful for experiments in high-performance reactors, transient test reactors, and critical mock-ups, which distinctly benefit from real-time flux measurement.

[0010] Finally, self-powered neutron detectors (SPND) incorporate neutron-sensitive materials that decay by beta or gamma-ray emission. The simplest versions of SPNDs rely on the direct measurement of the beta decay current following a neutron absorption [1]. In contrast to typical fission chambers, SPN detectors are typically very small, and require no applied bias. However, the output current from SPN detectors is very small, and does suffer a time delay due to the nuclear decay [1]. There are fast responding SPN detectors, but they are based on gamma-ray reactions, combined with neutron reactions, which confuse the actual source of the signal.
The gamma-ray sensitive SPN detectors are generally 100 times less sensitive to the radiation environment. Consequently, they are generally not used for reactor startup, shutdown, or quantitative transient measurements.

[0011] Gas-filled detectors are arranged in three various forms, those forms being ion chambers, proportional counters, and Geiger-Müller counters. Of these basic forms, the proportional counter design is often used as the fundamental instrument for a gas-filled neutron detector. Proportional counters rely upon avalanche multiplication in the gas to produce large electronic signals, each signal being proportional to the energy deposited in the detector chamber. Quite differently, ion chambers do not produce avalanche multiplication and Geiger-Müller counters produce excessive avalanching such that the electronic signal is no longer proportional to the energy deposited in the chamber.

[0012] Gas-filled proportional counters used for neutron detectors can be further subdivided into two types, those being detectors filled with a neutron reactive gas and those detectors that are coated with a neutron reactive material. Neutron interactions in either the neutron reactive gas or the neutron reactive coating eject energetic charged particles that create ionization in the detector gas. A voltage applied to the gas chamber causes the ions and electrons to move, and this ionization is subsequently measured as a current, thereby, indicating a neutron interaction occurred.

[0013] Gas detectors can be operated in pulse mode or current mode. Pulse mode is generally used in low to moderate radiation fields. In such a case, a single radiation quantum, such as an alpha particle, beta particle or gamma ray, interacts in the chamber volume, giving rise to an ionized cloud. The charge carriers drift apart, and as they move they induce current to flow to the device terminals; a charging circuit, usually consisting of a preamplifier and feedback loop, integrates the current and stores the charge, thereby producing a voltage potential. This voltage is measured as a single event, indicating that a single radiation quantum has been detected. The preamplifier circuit is subsequently discharged and reset, allowing the device to measure the next radiation interaction event. Hence, each voltage pulse from the detector indicates an individual radiation interaction event. Although extremely useful, there are drawbacks to this method. Should another radiation interaction occur while the detector is
integrating or discharging the current from a previous interaction event, the device may not, and usually does not, record the new interaction, a condition referred to as pulse pile up. The time duration in which a new pulse cannot be recorded is the detector recovery time, sometimes referred to as dead time. A pulse mode detector operated in low radiation fields has little problem with dead time count losses; however, a detector operated in high radiation fields may have significant dead time losses, thereby yielding an incorrect measurement of the radiation activity in the vicinity.

[0014] For high radiation fields, gas detectors are operated in current mode, in which the radiation induced current is measured on a current meter. Under such conditions, many interactions can occur in the device in short periods of time, and the current observed increases with total radiation exposure rate. Hence, current mode can be used to measure high radiation fields, with the magnitude of the current being a measure of the radiation induced ionization rate in the detector, thereby giving a measure of the radiation field in which the device is being operated. The disadvantage of current mode is that it does not identify individual radiation interactions.

[0015] Fig. 1 illustrates a gas-filled detector similar to that first explored by Geiger and Rutherford. The detector is exposed to directly ionizing radiation, which would include alpha-particles and beta-particles. Either of these particles can cause ionization in the gas-filled device, thereby, producing electron-ion pairs. Hence, there are both an absorber and an observable, so that to produce a radiation detector only a method is needed to measure the amount of ionization. Suppose the device is connected to a simple electrometer so as to measure the current produced by the motion of the electron-ion pairs. Without an applied voltage, the electron-ion pairs diffuse randomly in all directions and eventually recombine. As a result, the net current from the electrometer is zero. With an applied positive voltage to the thin wire of the device, or anode, the free electrons (negative charge) drift towards the anode and the free ions (positive charge) drift towards the detector wall. At low voltages, some measurable current is seen, yet considerable recombination still occurs, which is the recombination region identified as Region I in Fig. 2. As the voltage is increased, electron-ion pair separation becomes more efficient until practically no recombination occurs. Hence, the current measured is a measure of the total number of electron-
ion pairs formed, which is Region II of Fig. 2, and is referred to as the ionization chamber region.

[0016] As the voltage is increased further, the electrons gain enough kinetic energy to create more electron-ion pairs through impact ionization. This provides a mechanism for signal gain, often referred to as gas multiplication. As a result, the observed current increases as the voltage increases, but is still proportional to the energy of the original radiation particle. This multiplication occurs in Region III, the proportional region. Increasing the applied voltage further causes disproportional current increases to form, marked in Fig. 2 as Region IIia, beyond which, in Region IV, all currents, regardless of origin, radiation species or energies, are the same magnitude. Region IV is the Geiger-Miiller region. Finally, excessive voltage drives the detector into Region V where the voltage causes sporadic arcing and other spontaneous electron emissions to occur, hence causing continuous discharging in the detector. Gas detectors should not be operated in the continuous discharge region.

Summary of Example Embodiments of the Invention

[0017] A special type of coated gas-filled radiation detectors are fission chambers. These detectors have fissile or fissionable materials as coatings, which upon a neutron absorption, fission and emit two highly energetic fission products. The energy released per $^{235}$U fission is approximately 207 MeV, with ~168 MeV of the energy being carried as kinetic energy from the two fission fragments. The remaining 39 MeV is released in the form of gamma rays, fast neutrons, beta particles, and neutrinos, most of which escape detection. Usually two fission fragments share 168 MeV as kinetic energy, although there is a slight chance of triplet fission, where two relatively large fission products are released along with a much smaller fission product (such as a triton, Li ion, or B ion) [3].

[0018] These two fission fragments are released with different kinetic energies and masses, with average energies of 68.1 MeV and 99.2 MeV for each branch. The variety of possible fission fragments numbers in the hundreds with atomic masses ranging from 70 up to 170. The fission product mass and energy distributions for fissile materials $^{233}$U, $^{235}$U, $^{239}$Pu have similar distributions, although they are slightly different.
The large energy release from fission provides an attractive converter for neutron detectors, mainly because the energy from either fission product can be measured without the need for avalanche multiplication. As a result, most fission chambers are designed as ion chambers. The ranges of fission products in 1 atm of Ar are between 1.5 cm - 2.9 cm, depending on the mass and energy; hence many fission chambers are designed with dimensions on the same order. Upon nuclear fission, the fission fragments are ejected in approximately opposite directions, although the other energetic fission emissions cause a slight change in these trajectories. Consequently, like many other coated neutron detectors, only one of the fission products is likely to be measured. Theoretical models developed by Kahn et al. [4] predict the pulse-height spectra for a thin film coating of U0₂ on a surface within a gas detector, with a solid angle of ~2π, with a few select results shown in Fig. 3 as compared to measured pulse height spectra. For relatively thin films, the two fission fragment branches are clearly discernable. For thicker films, the energy distribution becomes skewed towards the lower energies, a consequence of energy self-absorption for fission products that lose energy as they transit the U0₂ film before emerging into the detector gas. Because the lightest and most energetic fission products can not reach the detector gas if born at a distance greater than ~8.0 µm, there is no practical reason to apply films any thicker. Hence, the thermal neutron detection efficiency for a ²³⁵U0₂-coated detector is limited to ≤ 0.5%, a value predicted by methods described by McGregor et al. [5]. Fission chambers with U metal instead of U0₂ are also manufactured, and have a higher density of U per unit volume. However, the fission product ranges in U are also shorter (≤ 6µm) than in U0₂; consequently, the resultant thermal neutron detection efficiencies are also ≤ 0.5%.

A new type of miniaturized fission chamber is the micro-pocket fission detector (MPFD). These devices are significantly smaller than common fission chambers, having physical dimensions of < 1 cm with gas volumes < 1.0 cm³ or less. Although the small volumes are incapable of absorbing the total energy from any of the fission products, the amount of energy absorbed is on the order of 3 MeV for all fission products, regardless of the branch [6]. The small volume ensures that background gamma rays and beta particles cannot deposit enough energy to be detected, usually depositing less than 1 keV. Alpha-particle emissions from the reactive or responsive coating can deposit more energy, but also is on the order of only 60 keV or less. Hence, simple pulse-height discrimination can be used to separate neutron induced events from
radiation background. MPFDs are designed with relatively low efficiency because they are deployed in high radiation environments, including inside the core of a nuclear reactor. Their small size allows for them to be inserted into tiny test ports without causing flux depression. Dead time is also less of an issue, mainly because the electron-ion drift times are much smaller for these detectors than traditional fission chambers. These detectors can operate in pulse mode for neutron fluxes ranging up to $10^{12} \text{ n cm}^{-2} \text{ s}^{-1}$ before showing significant dead-time effects. Described here are new designs for MPFDs that allow for extended performance in high radiation fields, which allow for pulse mode and current mode operation in neutron fluxes beyond $10^{12} \text{ n cm}^{-2} \text{ s}^{-1}$, a significant improvement from previous designs.

[0021] Described here is a novel type of radiation detector system that can be inserted into the core of a nuclear reactor, survive the harsh operating environment found within, return real-time count rate information, maintain a long detector lifetime, and provide count rate information relative to its position within the core. This detector has been developed to accomplish these goals with minimal cost and supporting electronics.

[0022] Having been fabricated from radiation-hard materials, and being designed for prolonged lifetime, MPFDs can be used in a wide range of capacities. Accurate, real-time flux measurements can drastically improve the effectiveness and safety of research involving high performance reactors, transient test reactors and critical mockups. Due to their small size, the use of MPFDs in transient power and research reactors allow for dense instrumentation inside a nuclear reactor core. Also, by strategically placing an array of MPFDs throughout the reactor core, a real-time flux map can be generated without significantly perturbing the neutron flux, mainly due to the small size of these new detectors.

[0023] MPFDs can also aid with out-of-core fuel management. The "once-through" fuel cycle policy in the U.S.A. currently requires spent fuel to be stored after use. While many other countries worldwide reprocess spent fuel, accurate analysis and monitoring of spent fuel is important whether reprocessed or stored. Burnup calculations of commercial fuel are typically based on an estimate from specialized computer codes. While these burnup estimates are sufficient for spent fuel storage, improved accuracy of real-time data will aid in validating the various computer codes used for transport, storage, and reprocessing of spent fuel, as well as
fissile material safeguards and evaluating the performance of new nuclear fuels. MPFDs can be integrated into a fuel assembly and used to calculate the integral and time-dependent irradiation exposure of the fuel in that region. The irradiation measurement from a MPFD in commercial power reactors could also provide more accurate input for burnup simulations of spent fuel than present methods.

[0024] MPFDs operate on similar principles as typical fission-chamber neutron detectors. By designing a very small gas detector, many disadvantages of typical fission chambers are avoided. Additionally, by using a loose-stack design where the detection gas of the MPFD is allowed to circulate within a larger container, the buildup of fission fragments in the detection gas is minimized, and the 'memory effect' previously described does not occur. Finally, by utilizing the numerous surfaces within the MPFD geometry, production of 'mixed-coated' devices is greatly simplified. Although possible, mixing materials into a single coating introduces significant production challenges. Instead, various materials may be deposited on different surfaces individually.

[0025] MPFDs vary from miniature fission chambers in several ways. First, MPFDs use a much smaller detection gas chamber than typical miniature fission chambers (< cm³ vs > cm³). Secondly, where miniature fission chambers are typically designed for short lifetimes, using enriched materials, MPFDs are being designed for extended life using mixed coatings of neutron reactive materials, including U, Th and Pu. The loose-stacked design of MPFDs poses a significant shift from the sealed design used for most fission chamber style neutron detectors. For example, a typical MPFD will be composed of 1 or more radiation-hard device substrates (i.e. ceramic) assembled together, or manufactured in such a way to create a detection gas chamber with a volume < 1 cm³. The detection gas chamber is open to the exterior of the MPFD sensor, but within a larger gas-filled enclosure, to allow detection gas to flow into and out of the chamber. One or more surfaces of the detection gas chamber are coated with neutron-sensitive material, the selection of which varies depending on desired device application. Finally, an anode and cathode are present, across which a voltage is applied to measure the ionization that occurs in the detection gas chamber due to fission fragment ionization. Numerous variations of the generic MPFD geometry are described in the following sections.
Small fission chambers with parallel contact designs have functioned as MPFDs in the past [6,7,9]; however there are multiple problems with sealing these small fission chambers and connecting wires to the conductive contacts. Unlike traditional fission chamber designs that have planar electrodes, usually coated with the neutron reactive material, a preferred embodiment of the present design has two or more wires oriented mostly parallel to each other that act as the electrodes. Further, the neutron reactive material is located near the electrode wires, but not upon them. Hence, there is no need to connect the signal wires to electrical contacts because the signal wires serve as both the electrodes and signal wires. There is no longer a need to seal the MPFD. Instead the pieces stack together and operate without a sealant. The entire structure can be inserted into a gas-filled tube, which is backfilled with an appropriate detector gas and sealed. The metallic tube can also function as a ground and RF shield for the detectors. A benefit of the design is that multiple pieces can be stacked to build multiple fission chambers, or several longer fission chambers composed of longer elements, upon a single string of wire electrodes. The multi-wire micro-pocket fission chamber, a preferred embodiment depicted in Fig. 4, has several surfaces upon which neutron reactive material (4) may be deposited, including the sides of the cavity substrate Fig. 4 (32), an inner surface of upper substrate Fig. 4 (34), and an inner surface of the lower substrate Fig. 4 (31). These multi-wire micro-pocket fission chambers can be fabricated in microscopic sizes that are capable of producing large signals from neutron interactions while remaining insensitive to other radiations such as alpha particles, beta particles, and gamma rays. By fabricating devices with thin neutron reactive films, detectors can operate in pulse-mode at high neutron fluxes (>10^{12} n cm^{-2} s^{-1}) without significant dead-time. Further, these multi-wire fission chambers can be fashioned in an array such that the array of detectors all share a common cathode wire while having independent anode wires.

The substrates are best constructed from materials that do not interact with neutrons. Construction materials of interest that have low neutron interaction cross sections include Si, SiO_{2}, Quartz, SiC, AlN, GaN, Al_{2}O_{3}, and MgO. Low interaction cross sections ensure that the detectors will not adversely affect the power and neutronics of the reactor core while being relatively radiation hard. Presently, Al_{2}O_{3} is used for MPFDs. However, the material is extremely hard (9 on the Mohs hardness scale) and mostly inert to chemical attack [10] and is thus difficult to machine into tiny parts. Unfortunately, the cost and difficulty of manufacturing
alumina-based MPFDs are both extreme, and a process to produce low-cost and reliable MPFDs is needed.

[0028] An alternative material of interest is the semiconductor Si. Si is readily etched by either plasma or wet etching, and, hence, detectors can be fashioned with common VLSI \textit{(i.e. very large scale integration)} processing techniques. Contact application can also be accomplished with physical vapor deposition with either evaporative or sputtering methods. Although Si can undergo neutron transmutation, the material serves as a mechanical substrate and not as an electronic medium; hence, transmutation is not an issue. Although Si is semiconductive, thereby, not having the high resistance needed for the substrate, a thick SiO\textsubscript{2} layer is easily grown on the substrate with common wet-oxide methods used to fabricate MOS \textit{(i.e. metal-oxide-semiconductor)} devices [11]. Other low cross section materials that are of interest include SiO\textsubscript{2} (glass), Quartz, SiC, AlN, GaN, and MgO. All of these materials can be used as alternative MPFD substrates because of their radiation hardness, reliability, and manufacturability.

[0029] The neutron reactive materials often require a sublayer be applied to aid attachment to the substrate. For instance, a thin Ti or Pt layer may be required to attach U, Th, or Pu to an insulating substrate. Sometimes a layering approach of multiple bonding layers is required to attach the neutron reactive film. Under some circumstances, a sublayer is not always required for the film application. For instance, application with physical vapor deposition methods such as evaporation or sputtering may not require a sub-layer. The neutron reactive coating must have sufficiently high neutron absorption to allow for reasonable neutron detection, yet not so large so as to burn-up the neutron reactive material rapidly. Reactive film candidates for the MPFDs include natural U, Pu, enriched \textsuperscript{235}U, \textsuperscript{232}Th, and \textsuperscript{242}Pu. The corresponding microscopic thermal neutron fission cross sections are 577 barns for pure \textsuperscript{235}U, and only 4 barns (E \textgreater 1.1\text{MeV}) for \textsuperscript{232}Th. MPFDs with both \textsuperscript{232}Th and \textsuperscript{235}U were reported to respond to both thermal and fast neutrons in a nuclear reactor [6,9,12].

[0030] The devices disclosed are unique because of their miniature size and rapid response, generally being \textless 1\text{cm} wide. The energy deposition and ranges of \textsuperscript{232}Th and \textsuperscript{235}U fission products in 1 atm of P-10 gas extend beyond several cm [13]. Only a fraction of energy for any fission fragment is deposited within a one-cm wide cavity of P-10 gas [13]. For MPFDs
with $^{235}$U as the reactive film, fission fragments from both branches (-95 MeV bromine, -60 MeV iodine, for example) will deposit of approximately 3 MeV of energy within a 500 micron wide pocket [6, 13]. Energies of such large magnitude are easily discriminated from background gamma rays, and the thin gas pocket requires only 25-200 volts operating bias. Construction materials with low gamma-ray absorption will reduce background interference.

[0031] In order to design MPFDs for long-term in-core deployment, the reactive material must be chosen carefully to ensure a relatively stable response over long periods of time. For commercial reactors, in-core detectors could be inserted for single cycles (about 18 months) or for the duration of an assembly's time in a reactor (about 5 years). Although any neutron-reactive material may be used for an MPFD, a combination of enriched uranium and thorium can be used to extend the detector life. By determining an optimum combination of these materials, the signal deviation over time (for a constant flux) can be reduced.

[0032] The MPFDs can be constructed using a loose stacking scheme, although sealed MPFDs will also operate properly. The loose stacking design (Fig. 4) has three MPFD pieces strung onto two conductive wires Fig. 4 (3). These wires no longer need to be attached or bonded directly to the assembly, a major difference from past designs. A voltage applied across the two wires produces an electric field inside the central pocket, formed by the center piece. The neutron reactive materials are plated on the inside of the top and/or bottom pieces. As a result, the neutron reactive material is no longer atop the conductive contacts, as reported and required in early generation designs [6,9,12]. The detector parts do not need to be bonded with cement, as with prior reported designs [6,9,12], because they are stacked and inserted inside a gas-filled tube.

[0033] MPFDs substrates can be etched with either dry-etching or wet-etching methods, thereby, greatly reducing cost and allowing for easy manufacturing. Of particular interest is the use of Si wafers, which can allow for mass production of MPFDs on Si wafers with the exact miniature MPFD features, and then subsequently sliced from the wafer. With the use of vapor vacuum bonding (i.e. vacuum bonding is performed with water vapor and no other adhesives), the entire MPFD can be manufactured at the wafer scale, with completed devices sliced from the bonded wafers. High-resistivity semiconductors, such as GaN, SiC and AlN, can be etched with
reactive ion etching and do not need an insulating coating (although an insulating layer can be applied with physical vapor deposition methods). A1N can also be etched with wet chemistry. Insulators such as SiO$_2$ can be wet etched to the proper MPFDs dimensions in relatively short time. The neutron reactive materials can be plated on the upper and lower MPFD pieces.

[0034] Thermocouple sensors can be added to monitor the temperature at the detector locations in the core. The entire array structure can be enclosed in a gas-filled tube, backfilled with a gas such as pure Ar.

[0035] Disclosed is a new type of miniaturized neutron detector suitable for applications in all types of nuclear reactors and solves many of the problems with present day in-core reactor instrumentation. The small size is non-intrusive, will not cause flux depression or unwanted perturbations in the neutron flux even for small research reactors, and will not significantly disrupt fluid flow in many cases. The compactness is particularly suited for Gen-IV and small modular reactors. With the capabilities and characteristics verified through this research, the detectors can be incorporated into power reactor cores, thereby, offering real-time flux and power profiling. Such applications would be the basis for a follow-on study. Inclusion of thermocouples in with the MPFDs adds information on the reactor thermal profile. Detector arrays distributed within a core allow for the development of core power maps. A list of advantages of the disclosed invention include:

1. Compact size - the dimensions are small < 1 cm.

2. Extreme radiation hardness - the gas and substrate construction do not suffer radiation damage.

3. Thermally resistant - the devices can be manufactured from high-temperature ceramics or high temperature radiation resistant materials.

4. Gamma-ray insensitive - the detection gas, small size, and light material composition all work to make the device very gamma-ray insensitive, hence the neutron signals are easily discernable from background gamma-ray interference.

5. Inexpensive - construction is straightforward and requires inexpensive materials.
6. Large signals - the reaction products are highly energetic and the output signals easy to detect.

7. Deployment at power reactors - Successful demonstration of the MPFD concept can lead to detector usage in commercial reactors, research reactors, small modular reactors and Gen-IV reactors.

8. Core imaging – The devices can be used to back-project the fuel power densities from within a commercial, research, or Gen-IV nuclear reactor.

9. Power and thermal monitoring - The materials and devices are particularly suited for the environment expected inside a Gen-IV reactor, including temperatures above 400°C, pressures >2300 psi while under neutron irradiation in a beam port.

10. Thermocouples can be intertwined with the MPFDs to provide temperature information.

11. Compatible with advanced reactor materials - The devices designed for the project will fulfill a need for Gen-IV reactors using advanced materials. Gen-IV reactors need in-core detectors for (a) initial monitoring studies of prototypes, and (b) control of commercial units when they are deployed.

12. The small devices are fast and can follow reactor transients. They can be used at reactor startup and shutdown while continuing to produce a signal representative of the actual reactor power level.

[0036] The MPFD technology provides a new power-monitoring device for research nuclear reactors and commercial nuclear reactors extending to Gen-IV reactors. The detectors can be inserted with fuel bundles of commercial reactors and operated during an entire fuel cycle.
Brief Description of the Figures

[0037] FIG 1 shows a diagram of a coaxial gas-filled radiation detector; this configuration is used for a variety of gas-filled detectors, including ion chambers, proportional counters, and Geiger-Müller counters;

[0038] FIG. 2. shows the gas-filled detector pulse height response as a function of applied voltage, showing the five major operational regions;

[0039] FIGS 3A-3D show calculated and experimentally measured pulse height spectra of fission fragments from UO$_2$ film thicknesses of 28.6 nm, 714 nm, 2.53 µm and 7.54 µm, respectively, data from [4];

[0040] FIG. 4 is an exploded isometric view of a first embodiment of a Multi-Wire Micro-Pocket Fission Detector;

[0041] FIG. 5 is an isometric view of the first embodiment of a Multi-Wire Micro-Pocket Fission Detector;

[0042] FIG. 6 is a cross-sectional view of the first embodiment of a Multi-Wire Micro-Pocket Fission Detector;

[0043] FIG. 7 is a cross-sectional view the first embodiment of a Multi-Wire Micro-Pocket Fission Detector;

[0044] FIG. 8 is a cross-sectional view of the first embodiment of a Multi-Wire Micro-Pocket Fission Detector;

[0045] FIG. 9 is a cross-sectional view of the first embodiment of a Multi-Wire Micro-Pocket Fission Detector;

[0046] FIG. 10 is a cross-sectional view of the first embodiment of a Multi-Wire Micro-Pocket Fission Detector;

[0047] FIG. 11 is a cross-sectional view of the first embodiment of a Multi-Wire Micro-Pocket Fission Detector;
FIG. 12 is a cross-sectional view of the first embodiment of a Multi-Wire Micro-Pocket Fission Detector;

FIG. 13 is a cross-sectional view of a second embodiment of a Multi-Wire Micro-Pocket Fission Detector;

FIG. 14 is an isometric view of the second embodiment of a Multi-Wire Micro-Pocket Fission Detector;

FIG. 15 is a top view of a third embodiment of a Micro-Fission Detector;

FIG. 16 is an exploded isometric view of the third embodiment of the Micro-Fission Detector;

FIG. 17 is a cross-sectional view of the third embodiment of the Micro-Fission Detector;

FIG. 18 is an isometric view of a Stacked-Concentric Micro-Fission Detector assembly;

FIG. 19 is an exploded isometric view of the Stacked-Concentric Micro-Fission Detector assembly;

FIG. 20 is a cross-sectional view of the Stacked-Concentric Micro-Fission Detector assembly;

FIG. 21 is an isometric view of the Micro-Pocket Fission Detector assembly;

FIG. 22 is an exploded isometric view of the Micro-Pocket Fission Detector assembly;

FIG. 23 is a cross-sectional view of the Micro-pocket Fission Detector assembly;

FIG. 24 is an exploded isometric view of the Micro-Pocket Fission Detector assembly with a fully-coated gas volume;
FIG. 25 is a cross-sectional view of the Micro-Pocket Fission Detector assembly with a fully-coated gas volume;

FIG. 26 is an exploded isometric view of the Micro-Pocket Fission Detector assembly with a porous and/or low-density neutron conversion material;

FIG. 27 is a cross-sectional view of the Micro-Pocket Fission Detector assembly with a porous and/or low-density neutron conversion material;

FIG. 28 is an exploded isometric view of the Micro-Pocket Fission Detector assembly with a grown neutron conversion material;

FIG. 29 is a cross-sectional view of the Micro-Pocket Fission Detector assembly with a grown neutron conversion material;

FIG. 30 is an isometric view of the Micro-Pocket Fission Detector assembly with a channeled electric insulator;

FIG. 31 is an exploded isometric view of the Micro-Pocket Fission Detector assembly with a channeled electric insulator;

FIG. 32 is a cross-sectional view of the Micro-Pocket Fission Detector assembly with a channeled electric insulator;

FIG. 33 is an exploded isometric view of the Micro-Pocket Fission Detector assembly with a perforated electric insulator;

FIG. 34 is a cross-sectional view of the Micro-Pocket Fission Detector assembly with a perforated electric insulator;

FIG. 35 is an additional exploded isometric view of the Micro-Pocket Fission Detector assembly with a trenched, perforated electric insulator;

FIG. 36 is an additional cross-sectional view of the Micro-Pocket Fission Detector assembly with a trenched, perforated electric insulator;
FIG. 37 is an isometric view of the Two-Piece Micro-Pocket Fission Detector assembly;

FIG. 38 is an exploded isometric view of the Two-Piece Micro-Pocket Fission Detector assembly;

FIG. 39 is a cross-sectional view of the Two-Piece Micro-Pocket Fission Detector assembly;

FIG. 40 is an isometric view of the Interlaced Two-Piece Micro-Pocket Fission Detector assembly;

FIG. 41 is an exploded isometric view of the Interlaced Two-Piece Micro-Pocket Fission Detector assembly; and

FIG. 42 is a cross-sectional view of the Interlaced Two-Piece Micro-Pocket Fission Detector assembly.

Detailed Description of the Preferred Embodiments

FIGURE 1 is a prior art depiction of a coaxial gas-filled radiation detector, showing the main components of an anode, cathode and radiation induced ionization. The free electrons and positive ions are drifted through the chamber by an externally applied bias voltage. The motion of the free charges induces a current to flow in the circuit, which can be measured by an externally connected circuit.

FIGURE 2 is a depiction of the five voltage operating regions of a gas-filled radiation detector. Region I is referred to as the recombination region, where the voltage is insufficient to separate the electrons and positive before substantial recombination occurs. Recombined charges are neutralized, and therefore no longer influenced by the externally applied voltage. Region II is the ion chamber region, where the electric field is high enough to prevent almost all recombination, thereby, allowing for collection of the electrons and positive ions. Region III is the proportional counter region, where the electric field is high enough to produce gain through impact ionization, while retaining output signals proportional to the energy deposited in the detector. Region IV is the Geiger-Miiller region, where the avalanching
produced space charge that limits the total pulse observed, consequently causing all pulses to be of nearly the same magnitude regardless of the type or energy of the radiation. Region V is the continuous discharge region, where uncontrolled avalanched multiplication takes place, a condition that can damage the detector.

[0081] FIGURE 3 is a display of data from reference [4], showing the effect of pulse height resolution as a function of the fissionable deposit thickness within a common fission chamber. In the figure, the fissionable material was U0.2. Shown in Fig. 3a is a pulse height spectrum from a fission chamber with a relatively thin coating of U0.2, in which both fission product branches are clearly visible. As the thickness of the fissionable material is increased, depicted in Fig. 3b - 3d, fission product self-absorption effects degrade energy resolution, although the detector counting efficiency increases. Film thicknesses greater than the maximum fission product ranges cause a reduction in detection efficiency and are generally avoided.

[0082] FIGURE 4 is an exploded isometric view of the Multi-Wire Micro-Pocket Fission Detector (17) with a neutron conversion material (4). The detector is comprised of an upper substrate piece (34), cavity substrate piece (32) and a bottom substrate piece (31). Electrode wires (3) pass through holes (30) in the upper substrate (34), lower substrate (31) and open chamber of cavity (33) in the cavity substrate (32). Neutrons are converted into charged particle reaction products in the conversion material (4) which then ionize the gas in the cavity (33) between the electrodes (3) within the cavity substrate (32). The electron-ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is measured through the wire electrodes (3).

[0083] FIGURE 5 is an isometric view of the Multi-Wire Micro-Pocket Fission chamber of Fig. 4 after assembly. The parts or pieces 31, 32 and 34 can be fastened or cemented together, or may remain unattached and free floating. In either case, the gas within the detector is the medium ionized by the reaction products emitted from the neutron reactive or responsive material.

[0084] FIGURE 6 is a cross-sectional view of the Multi-Wire Micro-Pocket Fission Detector (17) with a neutron conversion material (4). The detector is comprised of an upper substrate (34), cavity substrate (32) and a bottom substrate (31). Electrode wires (3) pass through
holes (30) in the upper substrate (34), lower substrate (31) and open cavity (33) in the cavity substrate (32). Neutrons are converted into charged particle reaction products in the conversion material (4) which then ionize the gas in the cavity (33) between the electrodes (3) within the cavity substrate (32). The electron-ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is measured through the wire electrodes (3). The depiction in Fig. 6 has the neutron reactive material (4) coated upon the bottom substrate (31), although the neutron reactive material (4) can also be applied to the upper substrate (34).

[0085] FIGURE 7 is a cross-sectional view of the Multi-Wire Micro-Pocket Fission Detector (17) with a neutron conversion material (4a & 4b) deposited on multiple surfaces. The detector is comprised of an upper substrate (34), cavity substrate (32) and a bottom substrate (31). Electrode wires (3) pass through holes (30) in the upper substrate (34), lower substrate (31) and open cavity (33) in the cavity substrate (32), and neutron conversion material (4a & 4b), which may consist of the same or different materials, all assembled with a detector gas pocket. The neutron conversion materials (4a & 4b) must not create an electronic short between the electrode materials (3) and may be deposited on other surfaces (not limited by those depicted) within the detector. Neutrons are converted into charged reaction products in the conversion materials (4a & 4b) which then ionize the gas between the electrodes (3). The electron-ion pairs are then drifted to the electrodes (3) using an applied bias, generating a pulse signal that is measured through the wire electrodes (3).

[0086] FIGURE 8 is a cross-sectional view of the Multi-Wire Micro-Pocket Fission Detector (17) with a neutron conversion material (4a & 4b) deposited on recessed regions (41) on multiple surfaces. The recess works to reduce conduction paths between the neutron conversion materials (4a & 4b) and the conductive wires (3). The detector is comprised of an upper substrate (34), cavity substrate (32) and a bottom substrate (31). Electrode wires (3) pass through holes (30) in the upper substrate (34), lower substrate (31) and open cavity (33) in the cavity substrate (32). The neutron conversion material (4a & 4b), which may consist of the same or different materials, is assembled within a detector gas pocket. The neutron conversion materials (4a & 4b) must not create an electronic short between the electrode materials (3) and may be deposited on other surfaces (not limited by those depicted) within the detector. Neutrons
are converted into charged reaction products in the conversion materials (4a & 4b) which then ionize the gas between the electrodes (3). The electron-ion pairs are then drifted to the electrodes (3) using an applied bias, generating a pulse signal that is measured through the wire electrodes (3).

[0087] FIGURE 9 is a cross-sectional view of the Multi-Wire Micro-Pocket Fission Detector (17) with a neutron conversion material (4a & 4b) on multiple surfaces. An insulating coating (42), such as aluminum oxide (Al₂O₃), silicon nitride (Si₃N₄), or silicon dioxide (SiO₂) is deposited over the neutron conversion material (4a & 4b). The insulating coating (42) works to reduce conduction paths between the neutron conversion materials (4a & 4b) and the conductive wires (3). The detector is comprised of an upper substrate (34), cavity substrate (32) and a bottom substrate (31). Electrode wires (3) pass through holes (30) in the upper substrate (34), lower substrate (31) and open cavity (33) in the cavity substrate (32), and also holes (43) through the insulating coating (42). The neutron conversion material (4a & 4b), which may consist of the same or different materials, is assembled within a detector gas pocket. The neutron conversion materials (4a & 4b) must not create an electronic short between the electrode materials (3) and may be deposited on other surfaces (not limited by those depicted) within the detector. Neutrons are converted into charged reaction products in the conversion materials (4a & 4b) which then ionize the gas between the electrodes (3). The electron-ion pairs are then drifted to the electrodes (3) using an applied bias, generating a pulse signal that is measured through the wire electrodes (3).

[0088] FIGURE 10 is a cross-sectional view of the Multi-Wire Micro-Pocket Fission Detector (17) with a neutron conversion material (4a & 4b) on multiple surfaces. Insulating spacers (44), such as aluminum oxide (Al₂O₃), silicon nitride (Si₃N₄), or silicon dioxide (SiO₂), are placed around the conductive wires (3). The insulating spacers (44) work to reduce conduction paths between the neutron conversion materials (4a & 4b) and the conductive wires (3). The detector is comprised of an upper substrate (34), cavity substrate (32) and a bottom substrate (31). Electrode wires (3) pass through holes (30) in the upper substrate (34), lower substrate (31) and open cavity (33) in the cavity substrate (32), and also the insulating spacers (44). The neutron conversion material (4a & 4b), which may consist of the same or different materials, is assembled within a detector gas pocket. The neutron conversion materials (4a &
4b) must not create an electronic short between the electrode materials (3) and may be deposited on other surfaces (not limited by those depicted) within the detector. Neutrons are converted into charged reaction products in the conversion materials (4a & 4b) which then ionize the gas between the electrodes (3). The electron-ion pairs are then drifted to the electrodes (3) using an applied bias, generating a pulse signal that is measured through the wire electrodes (3).

[0089] FIGURE 11 is a cross-sectional view of the Multi-Wire Micro-Pocket Fission Detector (17) with a neutron conversion material (4a & 4b) on multiple surfaces. Insulating ridges (45) are fashioned in the substrate around the conductive wires (3). The insulating ridges (45) work to reduce conduction paths between the neutron conversion materials (4a & 4b) and the conductive wires (3). The detector is comprised of an upper substrate (34), cavity substrate (32) and a bottom substrate (31). Electrode wires (3) pass through holes (30) in the upper substrate (34), lower substrate (31) and open cavity (33) in the cavity substrate (32). The neutron conversion material (4a & 4b), which may consist of the same or different materials, is assembled within a detector gas pocket. The neutron conversion materials (4a & 4b) must not create an electronic short between the electrode materials (3) and may be deposited on other surfaces (not limited by those depicted) within the detector. Neutrons are converted into charged reaction products in the conversion materials (4a & 4b) which then ionize the gas between the electrodes (3). The electron-ion pairs are then drifted to the electrodes (3) using an applied bias, generating a pulse signal that is measured through the wire electrodes (3).

[0090] FIGURE 12 is a cross-sectional view of the Multi-Wire Micro-Pocket Fission Detector (17) with a neutron conversion material (4a & 4b) on multiple surfaces. An insulating ridge (46) surrounds the neutron reactive material (4a & 4b). The insulating ridge (46) works to reduce conduction paths between the neutron conversion materials (4a & 4b) and the conductive wires (3). The detector is comprised of an upper substrate (34), cavity substrate (32) and a bottom substrate (31). Electrode wires (3) pass through holes (30) in the upper substrate (34), lower substrate (31) and open cavity (33) in the cavity substrate (32). The neutron conversion material (4a & 4b), which may consist of the same or different materials, is assembled within a detector gas pocket. The neutron conversion materials (4a & 4b) must not create an electronic short between the electrode materials (3) and may be deposited on other surfaces (not limited by those depicted) within the detector. Neutrons are converted into charged reaction products in the
conversion materials (4a & 4b) which then ionize the gas between the electrodes (3). The electron-ion pairs are then drifted to the electrodes (3) using an applied bias, generating a pulse signal that is measured through the wire electrodes (3).

[0091] FIGURE 13 is a isometric view of the Single-Piece Multi-Wire Micro-Pocket Fission Detector (18) with a neutron conversion material deposited on multiple surfaces (4a & 4b). The detector is comprised of a dielectric substrate (2), electrode materials (3), and neutron conversion material (4a & 4b), which may consist of the same or different materials, all assembled with a detector gas pocket. The neutron conversion materials (4a & 4b) must necessarily not create an electronic short between the electrode materials (3) and may be deposited on other surfaces (not limited by those depicted) within the detector. Neutrons are converted into charged reaction products in the conversion materials (4a & 4b) which then ionize the gas between the electrodes (3). The electron-ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the wire electrodes (3).

[0092] FIGURE 14 a cross-sectional view of the Single-Piece Multi-Wire Micro-Pocket Fission Detector (18) of Fig. 13 with a neutron conversion material deposited on multiple surfaces (4a & 4b). The detector is comprised of a dielectric substrate (2), electrode materials (3), and neutron conversion material (4a & 4b), which may consist of the same or different materials, all assembled with a detector gas pocket. The neutron conversion materials (4a & 4b) must necessarily not create an electronic short between the electrode materials (3) and may be deposited on other surfaces (not limited by those depicted) within the detector. Neutrons are converted into charged reaction products in the conversion materials (4a & 4b) which then ionize the gas (5) between the electrodes (3). The electron-ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the wire electrodes (3).

[0093] FIGURE 15 is an isometric view of a Micro-Structured, Micro-Pocket Fission Detector (1), suspended in a detector gas (5). The device consists of a single piece of dielectric substrate (2) that has surface perforations (50). The perforations (50) contain the electrodes (3), separated by an electrically-insulating layer (6), and neutron-conversion materials (4) necessary
for device functionality. Neutrons are converted into charged reaction products in the conversion material (4) which then ionize the surrounding gas (5). The electron-ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the contacts.

[0094] FIGURE 16 is an exploded isometric view of the Micro-Structured, Fission Detector (1), suspended in a detector gas (5). The device consists of a single piece of dielectric substrate (2) that has had perforations (50) etched into its surface. The perforations (50) contain the electrode (3), separated by an electrically-insulating layer (6), and neutron-conversion materials (4) necessary for device functionality. Neutrons are converted into charged reaction products in the conversion material (4) which then ionize the surrounding gas (5). The electron-ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the contacts.

[0095] FIGURE 17 is a cross-sectional view of the Micro-Structured, Fission Detector (1), suspended in a detector gas (5). The device consists of a single piece of dielectric substrate (2) that has had perforations (50) etched into its surface. The perforations (50) contain the electrode (3), separated by an electrically-insulating layer (6), and neutron-conversion materials (4) necessary for device functionality. Neutrons are converted into charged reaction products in the conversion material (4) which then ionize the surrounding gas (5). The electron-ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the contacts.

[0096] FIGURE 18 is an isometric view of a Stacked-Concentric, Fission Detector (7), enveloped in a detector gas (5). The device is comprised of many individual detectors, each stacked one on top of the other, separated by an insulating layer (8). The individual detectors are comprised of a dielectric substrate (2), electrode materials (3), neutron conversion material (4), all assembled and suspended in a detector gas (5). Neutrons are converted into charged reaction products in the conversion material (4) which then ionize the surrounding gas (5). The electron-ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the contacts (9).
FIGURE 19 is an exploded isometric view of a Stacked-Concentric, Micro-Pocket Fission Detector (7), enveloped in a detector gas (5). The device is comprised of many individual detectors, each stacked one on top of the other, separated by an insulating layer (8). The individual detectors are comprised of a dielectric substrate (2), electrode materials (3), neutron conversion material (4), all assembled and suspended in a detector gas (5). Neutrons are converted into charged reaction products in the conversion material (4) which then ionize the surrounding gas (5). The electron-ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the contacts (9).

FIGURE 20 is a cross-sectional view of a Stacked-Concentric, Micro-Pocket Fission Detector (7) of Figs. 18 and 19, enveloped in a detector gas (5). The device is comprised of many individual detectors, each stacked one on top of the other, separated by an insulating layer (8). The individual detectors are comprised of a dielectric substrate (2), electrode materials (3), neutron conversion material (4), all assembled and suspended in a detector gas (5). Neutrons are converted into charged reaction products in the conversion material (4) which then ionize the surrounding gas (5). The electron-ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the contacts (9).

FIGURE 21 is an isometric view of a Micro-Pocket Fission Detector (10). The detector is comprised of a dielectric substrate (2), electrode materials (3) separated by an insulating material (8), neutron conversion material (4), all assembled with a detector gas pocket. Neutrons are converted into charged reaction products in the conversion material (4) (Figure 21) which then ionize the gas (5) between the electrodes. The electron-ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the contacts (9).

FIGURE 22 is an exploded isometric view of a Micro-Pocket Fission Detector (10). The detector is comprised of a dielectric substrate (2), electrode materials (3) separated by an insulating material (8), neutron conversion material (4), all assembled with a detector gas pocket. Neutrons are converted into charged reaction products in the conversion material (4) which then ionize the gas (5) between the electrodes. The electron-ion pairs induced in the
pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the contacts (9).

[0101] FIGURE 23 is a cross-sectional view of a Micro-Pocket Fission Detector (10) of Figs. 21 and 22. The detector is comprised of a dielectric substrate (2), electrode materials (3) separated by an insulating material (8), neutron conversion material (4), all assembled with a detector gas pocket. Neutrons are converted into charged reaction products in the conversion material (4) which then ionize the gas (5) between the electrodes. The electron-ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the contacts (9).

[0102] FIGURE 24 is an exploded isometric view of a Micro-Pocket Fission Detector (10) with the neutron conversion material (4) completely coating the detector gas pocket. The detector is comprised of a dielectric substrate (2), electrode materials (3) separated by an insulating material (8), neutron conversion material (4), all assembled with a detector gas pocket. Neutrons are converted into charged reaction products in the conversion material (4) which then ionize the gas (5) between the electrodes. The electron-ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the contacts (9).

[0103] FIGURE 25 is a cross-sectional view of a Micro-Pocket Fission Detector (10) of Fig. 24 with the neutron conversion material (4) completely coating the detector gas pocket. The detector is comprised of a dielectric substrate (2), electrode materials (3) separated by an insulating material (8), neutron conversion material (4), all assembled with a detector gas pocket. Neutrons are converted into charged reaction products in the conversion material (4) which then ionize the gas (5) between the electrodes. The electron-ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the contacts (9).

[0104] FIGURE 26 is an exploded isometric view of a Micro-Pocket Fission Detector (10) with a porous and/or low-density neutron conversion material (11). The detector is comprised of a dielectric substrate (2), electrode materials (3) separated by an insulating material (8), neutron conversion material (4), all assembled with a detector gas pocket. Neutrons are
converted into charged reaction products in the conversion material (4) which then ionize the gas (5) between the electrodes. The electron-ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the contacts.

[0105] FIGURE 27 is a cross-sectional view of a Micro-Pocket Fission Detector (10) of Fig. 26 with a porous and/or low-density neutron conversion material (11). The detector is comprised of a dielectric substrate (2), electrode materials (3) separated by an insulating material (8), neutron conversion material (11), all assembled with a detector gas pocket. Neutrons are converted into charged reaction products in the conversion material (11) which then ionize the gas (5) between the electrodes. The electron-ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the contacts (9).

[0106] FIGURE 28 is an exploded isometric view of a Micro-Pocket Fission Detector (10) with an extended grown neutron conversion material (12). The detector is comprised of a dielectric substrate (2), electrode materials (3) separated by an insulating material (8), neutron conversion material (12), all assembled with a detector gas pocket. Neutrons are converted into charged reaction products in the conversion material (12) which then ionize the gas (5) between the electrodes. The electron-ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the contacts (9).

[0107] FIGURE 29 is a cross-sectional view of a Micro-Pocket Fission Detector (10) of Fig. 28 with an extended grown neutron conversion material (12). The detector is comprised of a dielectric substrate (2), electrode materials (3) separated by an insulating material (8), neutron conversion material (12), all assembled with a detector gas pocket. Neutrons are converted into charged reaction products in the conversion material (12) which then ionize the gas (5) between the electrodes. The electron-ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the contacts.

[0108] FIGURE 30 is an isometric view of a Micro-Pocket Fission Detector (10) with a neutron conversion material (4). The detector is comprised of a dielectric substrate (2), electrode materials (3) separated by a channeled insulating material (13), neutron conversion material (4),
all assembled with a detector gas pocket. Neutrons are converted into charged reaction products in the conversion material (4) which then ionize the gas (5) between the electrodes. The electron-ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the contacts (9).

[0109] FIGURE 31 is an exploded isometric view of a Micro-Pocket Fission Detector (10) with a neutron conversion material (4). The detector is comprised of a dielectric substrate (2), electrode materials (3) separated by a channeled insulating material (13), neutron conversion material (4), all assembled with a detector gas pocket. Neutrons are converted into charged reaction products in the conversion material (4) which then ionize the gas (5) between the electrodes. The electron-ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the contacts (9).

[0110] FIGURE 32 is a cross-sectional view of a Micro-Pocket Fission Detector (10) of Fig. 30 and 31 with a neutron conversion material (4). The detector is comprised of a dielectric substrate (2), electrode materials (3) separated by a channeled insulating material (13), neutron conversion material (4), all assembled with a detector gas pocket. Neutrons are converted into charged reaction products in the conversion material (4) which then ionize the gas (5) between the electrodes. The electron-ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the contacts (9).

[0111] FIGURE 33 is an exploded isometric view of a Micro-Pocket Fission Detector (10) with a neutron conversion material (4) lining the inner walls of the perforated channeled insulating material (14). The detector is comprised of a dielectric substrate (2), electrode materials (3) separated by a perforated channeled insulating material (14), neutron conversion material (4), all assembled with a detector gas pocket. Neutrons are converted into charged reaction products in the conversion material (4) which then ionize the gas (5) between the electrodes. The electron-ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the contacts (9).

[0112] FIGURE 34 is a cross-sectional view of a Micro-Pocket Fission Detector (10) of Fig. 33 with a neutron conversion material (4) lining the inner walls of the perforated channeled insulating material (14). The detector is comprised of a dielectric substrate (2), electrode
materials (3) separated by a perforated channeled insulating material (14), neutron conversion material (4), all assembled with a detector gas pocket. Neutrons are converted into charged reaction products in the conversion material (4) which then ionize the gas (5) between the electrodes. The electron-ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the contacts (9).

[0113] FIGURE 35 is an exploded isometric view of a Micro-Pocket Fission Detector (10) with a neutron conversion material (4) lining the inner walls of the perforated channeled insulating material (14). The perforations (50) are of a trenched geometry. The detector is comprised of a dielectric substrate (2), electrode materials (3) separated by a perforated channeled insulating material (14), neutron conversion material (4), all assembled with a detector gas pocket. Neutrons are converted into charged reaction products in the conversion material (4) which then ionize the gas (5) between the electrodes. The electron-ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the contacts (9).

[0114] FIGURE 36 is a cross-sectional view of a Micro-Pocket Fission Detector (10) of Fig. 35 with a neutron conversion material (4) lining the inner walls of the perforated channeled insulating material (14). The perforations (50) are of a trenched geometry. The detector is comprised of a dielectric substrate (2), electrode materials (3) separated by a perforated channeled insulating material (14), neutron conversion material (4), all assembled with a detector gas pocket. Neutrons are converted into charged reaction products in the conversion material (4) which then ionize the gas (5) between the electrodes. The electron-ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the contacts (9).

[0115] FIGURE 37 is an isometric view of a Two-Piece Micro-Pocket Fission Detector (15) of Figs. 39 and 38 with a neutron conversion material (4). The detector is comprised of a dielectric substrate (2), electrode materials (3), neutron conversion material (4), all assembled with a detector gas pocket. Neutrons are converted into charged reaction products in the conversion material (4) which then ionize the gas (5) between the electrodes. The electron-ion
pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the contacts (9).

[0116] FIGURE 38 is an exploded isometric view of a Two-Piece Micro-Pocket Fission Detector (15) with a neutron conversion material (4). The detector is comprised of a dielectric substrate (2), electrode materials (3), neutron conversion material (4), all assembled with a detector gas pocket. Neutrons are converted into charged reaction products in the conversion material (4) which then ionize the gas (5) between the electrodes. The electron-ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the contacts (9).

[0117] FIGURE 39 is a cross-sectional view of a Two-Piece Micro-Pocket Fission Detector (15) with a neutron conversion material (4). The detector is comprised of a dielectric substrate (2), electrode materials (3), neutron conversion material (4), all assembled with a detector gas pocket. Neutrons are converted into charged reaction products in the conversion material (4) which then ionize the gas (5) between the electrodes. The electron-ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the contacts (9).

[0118] FIGURE 40 is an isometric view of the Interlaced Two-Piece Micro-Pocket Fission Detector (16) with a neutron conversion material (4). The detector is comprised of a dielectric substrate (2), electrode materials (3), neutron conversion material (4), all assembled with a detector gas pocket. Neutrons are converted into charged reaction products in the conversion material (4) which then ionize the gas (5) between the electrodes. The electron-ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the contacts.

[0119] FIGURE 41 is an exploded isometric view of the Interlaced Two-Piece Micro-Pocket Fission Detector (16) with a neutron conversion material (4). The detector is comprised of a dielectric substrate (2), electrode materials (3), neutron conversion material (4), all assembled with a detector gas pocket. Neutrons are converted into charged reaction products in the conversion material (4) which then ionize the gas (5) between the electrodes. The electron-
ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the contacts.

[0120] FIGURE 42 is a cross-sectional view of the Interlaced Two-Piece Micro-Pocket Fission Detector (16) of Figs. 40 and 41 with a neutron conversion material (4). The detector is comprised of a dielectric substrate (2), electrode materials (3), neutron conversion material (4), all assembled with a detector gas pocket. Neutrons are converted into charged reaction products in the conversion material (4) which then ionize the gas (5) between the electrodes. The electron-ion pairs induced in the pocket are then swept to the electrodes (3) using an applied bias, generating a pulse signal that is read out through the contacts.
WHAT IS CLAIMED IS:

1. A device for detecting neutrons and configured to operate within a high-radiation environment to measure local neutron flux without significantly perturbing the local neutron flux, the device comprising:

   a gas-filled, micro-sized, reaction-product, detection chamber;

   an inert housing or substrate having at least one inner surface;

   neutron responsive material disposed on or near the at least one inner surface and at least partially defining the chamber, the material being responsive or reactive to neutrons absorbed thereby for releasing ionizing radiation reaction products into the gas within the chamber to ionize the gas and create ionization products; and

   a plurality of electrodes including an anode and a cathode for creating an electric field within the chamber upon application of a voltage to the electrodes, the electric field causing the ionization products to drift through the gas and induce charges at the anode and cathode to produce an electrical output signal at the electrodes.

2. The device as claimed in claim 1, wherein the volume of gas within the chamber is sized and shaped such that gamma rays, fast electrons and beta particles cannot readily deposit sufficient energy into the ionizing gas so as to register enough gas ionization to produce a recordable event at the electrodes.

3. The device as claimed in claim 1, wherein the chamber has physical dimensions < 1 cm with gas volume < 1.0 cm³.

4. The device as claimed in claim 1, wherein the device is operable in both pulse mode and current mode.
5. The device as claimed in claim 1, wherein the neutron responsive material is disposed on two or more inner surfaces of the substrate.

6. The device as claimed in claim 1, wherein neutron responsive material of a first type is disposed on a first inner surface of the substrate and neutron responsive material of a second type is disposed on a second inner surface of the substrate.

7. The device as claimed in claim 1, wherein the chamber is in fluid communication with an exterior of the substrate to allow the gas to flow into and out of the chamber.

8. The device as claimed in claim 1, wherein the electrodes are non-planar.

9. The device as claimed in claim 8, wherein the non-planar electrodes comprise substantially parallel, conductive wires and wherein the neutron responsive material is adjacent to each of the wires.

10. The device as claimed in claim 1, wherein the substrate includes a plurality of pieces which are loosely assembled together.

11. The device as claimed in claim 9, further comprising a gas-filled enclosure for housing the device of claim 1.
12. The device as claimed in claim 1, wherein the substrate includes a plurality of pieces strung onto the wires.

13. The device as claimed in claim 1, wherein the substrate is a single piece.

14. The device as claimed in claim 11, further comprising an insulating layer disposed on an inner surface of the substrate to electrically insulate the electrodes.

15. The device as claimed in claim 1, wherein the electrodes are separated by channeled insulating material assembled within the chamber.

16. The device as claimed in claim 1, wherein the neutron responsive material is disposed on the walls of the insulating material.

17. The device as claimed in claim 1, wherein the substrate includes two dielectric pieces.

18. The device as claimed in claim 17, wherein the dielectric pieces are interlaced.
19. The device as claimed in claim 1, wherein the neutron responsive material is comprised of one or a combination of materials containing B, $^{10}$B, Li, $^{6}$Li, U, $^{238}$U, $^{235}$U, Th, or Pu, Np, Am.

20. The device as claimed in claim 1, where more than one type of neutron responsive material is exposed to the detection chamber.

21. The device as claimed in claim 1, wherein the substrate is comprised of materials generally insensitive to neutron exposure, such as those with low neutron-absorption cross sections.

22. The device as claimed in claim 21, wherein the substrate materials are comprised of one or a combination of materials containing mostly Si, SiO$_2$, Quartz, SiC, A1N, GaN, A$_2$O$_3$, or MgO.

23. The device as claimed in claim 1, wherein the inert substrate comprises one or more pieces, etched partially and/or entirely through their thickness to produce a cavity upon which the neutron responsive and electrode materials are deposited.

24. The device as claimed in claim 1, wherein the anode and the cathode comprise one or more conductive plates.

25. The device as claimed in claim 1, wherein the anode and the cathode comprise one or more separate wires passing through the bulk of the device.
26. The device as claimed in claim 1, wherein the neutron responsive material is coated on one or more inner surfaces of the inert substrate and/or the electrodes.

27. The device as claimed in claim 1, wherein the neutron responsive material is suspended and/or grown within the volume of the chamber.

28. A neutron flux measurement subsystem including an array of loosely assembled devices of claim 1 to generate a flux map without significantly perturbing the neutron flux.

29. The subsystem as claimed in claim 28, wherein the output signals of the plurality of devices produce a 1-D array of point count-rate information.

30. The subsystem as claimed in claim 28, wherein the array of devices share a common anode or cathode.

31. The subsystem as claimed in claim 28, wherein the array of devices share a common anode and a common cathode.

32. A system including a plurality of subsystems of claim 28, wherein the output signals produce a 3-D array of point count-rate information.
33. The system as claimed in claim 32, wherein some or all of the devices share a common anode or cathode.

34. The system as claimed in claim 32, wherein some or all of the devices share a common anode and a common cathode.

35. The subsystem as claimed in claim 28, wherein a first one of the devices has a first type of neutron responsive material and a second one of the devices has a second type of neutron responsive material to provide count-rate information for various types of neutron fluxes.

36. The subsystem as claimed in claim 35, wherein the neutron responsive material of at least one of the devices is a non-thermal neutron responsive material such as $^{232}$Th or $^{242}$Pu.

37. The subsystem as claimed in claim 35 further including a device which has no neutron responsive material.

38. A nuclear fuel assembly comprising:

nuclear fuel elements; and

at least one device as claimed in claim 1 integrated with the nuclear fuel elements.

39. A subsystem comprising:

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at least one temperature measurement device; and

a device as claimed in claim 1 to provide coupled neutron count-rate and thermal information.
FIG. 1
(PRIOR ART)

FIG. 2
(PRIOR ART)
**FIG. 3A**
(PRIOR ART)

UO$_2$ thickness = 28.6 nm  
mass thickness = 0.0314 mg/cm$^2$

**FIG. 3B**
(PRIOR ART)

UO$_2$ thickness = 714 nm  
mass thickness = 0.7833 mg/cm$^2$

**FIG. 3C**
(PRIOR ART)

UO$_2$ thickness = 2.53 m  
mass thickness = 2.775 mg/cm$^2$

**FIG. 3D**
(PRIOR ART)

UO$_2$ thickness = 7.54 m  
mass thickness = 8.271 mg/cm$^2$
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - G01T 1/16 (2016.01)
CPC - G01T 3/00; G01T 3/006; G01T 3/02; G01T 7/00; G21D 1/00; Y02E 30/40; H01J 47/12
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
CPC: G01T 3/00; G01T 3/006; G01T 3/02; G01T 7/00; G21D 1/00; Y02E 30/40; H01J 47/12
IPC(8): G01T 1/16 (2016.01)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
IPC(8): G01T 1/16 (2016.01); USPC: 250/390.1.390.1 1,390.01,390.02; CPC: G01T 3/00; G01T 3/006; G01T 3/02; G01T 7/00; G21D 1/00; Y02E 30/40; H01J 47/12 (keyword limited; terms below)

Electronic database consulted during the international search (name of data base and, where practicable, search terms used)
PatBase; PubWEST; Google Scholar
Search Terms Used: neutron, flux, detector, sensor, gas, fluid, fission, fuel, inert, house, case, ionize, radiation, electrode, nuclear, current, mode, gamma, electric field, pulse mode

C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
<thead>
<tr>
<th>Category*</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>X A</td>
<td>US 2006/0043308 A1 (McGregor et al.) 02 March 2006 (02.03.2006), FIG 6, 7: para [0003], [0006], [0008], [0009], [0011]-[0013], [0073]-[0077], [0079], [0081], [0082], [0084], [0087], [0089] -[0091], [0099], [0100]</td>
<td>1-12, 14, 16, 19-23, 25-29, 32, 35-38</td>
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* Special categories of cited documents:
   'A' document defining the general state of the art which is not considered to be of particular relevance
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Date of the actual completion of the international search: 31 October 2016
Date of mailing of the international search report: 05 DEC 2016

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