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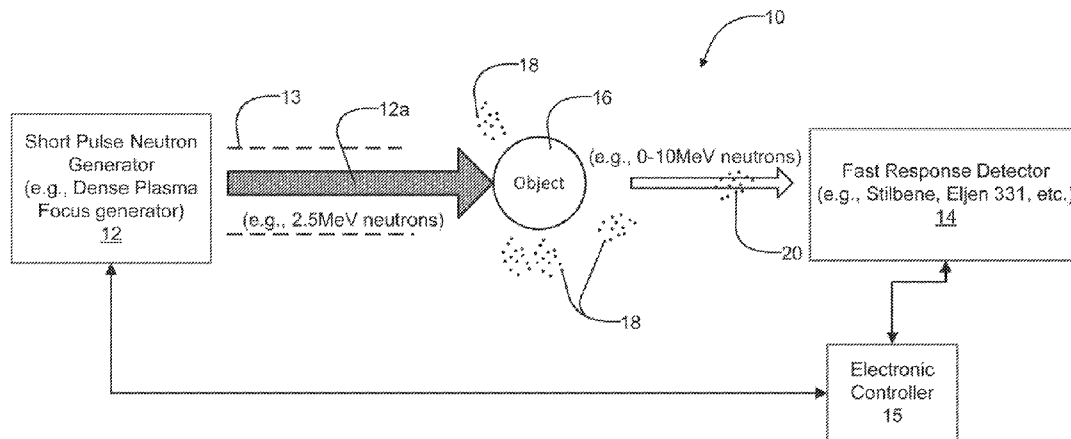


FIGURE 1

(57) Abstract: A system and method is disclosed for detecting fissionable materials. In one embodiment the system may incorporate a neutron pulse generator configured to generate multiple short pulses of neutrons, or a single pulse of sufficient intensity, in a vicinity of an object of interest. The source pulse of neutrons includes neutrons which each have a full width half maximum time duration of less than about 100 ns and a peak energy level no greater than about 20 MeV. A fast response detector is used which is able to detect single neutron events indicative of fission neutrons having been produced by the source pulse of neutrons interacting with fissionable material associated with the object of interest, and which arrive at the fast response detector within a predetermined time window immediately before arrival of the source neutron pulses.



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SYSTEM AND METHOD FOR FISSIONABLE MATERIAL DETECTION WITH A SHORT PULSE NEUTRON SOURCE

CROSS-REFERENCE TO RELATED APPLICATIONS

5 **[0001]** This application claims the benefit of United States Provisional Application No. 62/714,932 filed on August 6, 2018. The entire disclosure of the above application is incorporated herein by reference.

STATEMENT OF GOVERNMENT RIGHTS

10 **[0002]** The United States Government has rights in this invention pursuant to Contract No. DE-AC52-07NA27344 between the U.S. Department of Energy and Lawrence Livermore National Security, LLC, for the operation of Lawrence Livermore National Laboratory.

FIELD

15 **[0003]** The present disclosure relates to systems and methods for detecting fissionable material, and more particularly to a system and method for interrogating objects of interest remotely, using short duration, high intensity neutron pulses and fast response detectors, to detect whether the object of interest contains
20 fissionable material.

BACKGROUND

[0004] This section provides background information related to the present disclosure which is not necessarily prior art.

25 **[0005]** Emergency response and search applications often require on-site, unambiguous, and quick identification of objects of interest to determine if they contain fissionable material. Accordingly, remote detection of fissionable material, particularly when such material is shielded, is a problem of significant national security interest.

30 **[0006]** Remote detection of fissionable material is currently performed primarily either by passive means (e.g., gamma ray spectroscopy) or by active means. Active detection often requires knowledge of the surrounding environment, as, for example, differential die away from neutron interrogation would. Being able to

quickly and unambiguously detect fissionable material in the field will greatly simplify shipboard search, emergency response, and portal scanning applications.

[0007] Currently used and proposed methods for fissionable material detection involve Passive Gamma Ray Spectroscopy, Differential Die-Away, Gamma
5 Induced Neutron Analysis and Neutron Induced Gamma Analysis. Passive Gamma Ray Spectroscopy involves using a detector to identify the passively emitted gamma rays from fissionable materials. This method requires detectors to be deployed and does not require any active sources with the potential for harm to operators. This method, however, is often time consuming, cannot detect less active fissionable
10 materials, such as highly enriched uranium, and can be defeated by shielding radioactive materials.

[0008] Differential Die-Away (neutron induced neutron analysis) involves using a pulsed electronic neutron source to interrogate an object of interest. The fall-off of the neutron signal when the device is turned off, is sensitive to the presence of
15 fissionable material in the object of interest. This method is harder to shield than most gamma analysis regimes, however, interpretation of the data is dependent on the shape of the object and the surrounding environment. Accordingly, this method works better when these factors can be controlled, such as in cargo container inspection. At the present time, it is believed that differential die-away analysis has
20 only been fielded in highly controlled laboratory settings.

[0009] Gamma induced neutron analysis involves using a fast photon source to induce (gamma, n) reactions in the object/material of interest. Neutrons are then measured by a neutron sensitive detector. This method has the advantage of gamma sources being easier to turn on and off than neutron sources, and short-pulses increasing the signal above the background. However, this method is
25 expected to require significant research and development to make a rapidly-pulsed multi-pulse device. Additionally, the footprint of a fast photon source is typically quite large. At the present time, the most compact fast photon source would need to be transported on a large semi-truck.

[0010] Neutron induced gamma analysis involves the use of a neutron source which is used to interrogate an object, followed by gamma spectroscopy. This methodology solves the quiescent object problem in passive gamma ray spectroscopy, but it is still possible to shield the gamma signal with dense material.
30

[0011] In view of the foregoing, it will be appreciated that systems and methods are needed for reliably and unambiguously detecting the presence of fissionable material within, at or on an object of interest, and without the need for detailed information on other materials that may be in a vicinity of the object of interest, or advanced knowledge and consideration of the density of other objects in the vicinity of the object of interest, or the locations of such other objects or surfaces, or the geometry of the object of interest or the room in which it may be present. A further important consideration is in presenting a system that is of relatively compact dimensions, and relatively low in weight and power requirements, and which can be easily transported to sites where needed, and which is capable of detecting fissionable materials including shielded special nuclear materials (SNM), for various security and/or monitoring tasks.

SUMMARY

[0012] In one aspect the present disclosure relates to a system for detecting fissionable materials. The system may comprise a neutron pulse generator configured to generate multiple short pulses of neutrons, or a single pulse of sufficient intensity, in a vicinity of an object of interest. The source pulse of neutrons includes neutrons which each have a full width half maximum time duration of less than about 100 ns and a peak energy level no greater than about 20 MeV (e.g., the vast majority of the neutrons have energy below 20 MeV). A fast response detector may be included which is sensitive enough to detect single neutron events. Such events would be indicative of fission neutrons having been produced by the source pulse of neutrons interacting with fissionable material associated with the object of interest, if they arrive at the fast response detector within a predetermined time window immediately prior to the arrival of the source neutron pulses.

[0013] In another aspect the present disclosure relates to a system for detecting fissionable materials. The system may comprise a neutron pulse generator configured to generate multiple short pulses of neutrons, or a single pulse of sufficient intensity, in a vicinity of an object of interest, and directed at a first side of the object of interest. The multiple source pulses of neutrons each have a full width half maximum time duration of less than about 100 ns. A fast response detector may be included which is arranged remotely from the neutron pulse

generator and faces a second side of the object of interest generally longitudinally along a line-of-sight with the neutron pulse generator. The fast response detector is time aligned with the generation of the multiple short pulses of neutrons, and further is configured to detect one or more fission neutrons produced by the source pulse of neutrons interacting with the fissionable material associated with the object of interest, and arriving at the fast response detector within a predetermined time window immediately prior to the arrival of the source neutron pulses.

[0014] In still another aspect the present disclosure relates to a method for detecting a presence of a fissionable material associated with an object of interest. The method may comprise generating multiple short pulses of source neutrons, or a single pulse of sufficient intensity, in a vicinity of the object of interest, wherein the source neutrons have a full width half maximum time duration of less than about 100 ns and a peak energy level no greater than about 20 MeV (e.g., the vast majority of the neutrons have energy below 20 MeV). The method may further comprise using a fast response detector able to detect a single neutron event indicative of fission neutrons having been produced when the source neutrons interact with fissionable material associated with the object of interest, and wherein the fast response detector detects the single neutron event within a predetermined time window immediately prior to the arrival of the source neutron pulses.

DRAWINGS

[0015] The drawings described herein are for illustrative purposes only of selected embodiments and not all possible implementations and are not intended to limit the scope of the present disclosure. Corresponding reference numerals indicate corresponding parts throughout the several views of the drawings, in which:

[0016] Figure 1 is a schematic view of one embodiment of a system in accordance with the present disclosure;

[0017] Figure 2 shows a Monte Carlo N-particle (MCNP) simulation of the system operation for two unique scenarios, illustrating how the arrival of the fission neutrons induced at the object of interest is detected well before the scattered source neutrons;

[0018] Figure 3 is a graph showing an example of an early arrival fission neutron in time as compared to un-scattered neutrons; and

[0019] Figure 4 is a high-level flowchart setting forth various operations that may be performed by a system in accordance with the present disclosure.

DETAILED DESCRIPTION

5 **[0020]** Example embodiments will now be described more fully with reference to the accompanying drawings.

[0021] The present disclosure is directed to a method for reliably and quickly detecting the presence of fissionable material, without the limitations of existing methods which have previously been used for this purpose. Initially, a
10 monoenergetic or quasi-monoenergetic pulsed neutron source device is used to produce multiple neutron pulses, or a single pulse of sufficient intensity. In both cases, the sources turn on very quickly, within tens of nanoseconds. The simplest incarnation of a fast-turn-on pulse is an intense short pulse (e.g., <100 ns Full Width Half Maximum). For a sufficiently bright neutron source, the measurement could be
15 made with a single pulse.

[0022] It will be appreciated that no neutron source is truly monoenergetic. Even the Dense Plasma Focus (“DPF”) generator, which was used at Lawrence Livermore National Laboratory as the source neutron generator for the system and method of the present disclosure, is not truly monoenergetic, as there is some
20 thermal spread in the neutrons it produces. Additionally, one could have a neutron source, such as a deuterium-tritium source, which would emit neutrons at 14 MeV mostly, but also have a smaller population at mean energy of 2.45 MeV. In the strictest sense, this is not monoenergetic, but such a neutron source would still work satisfactorily as the neutron generator for the present system and method.
25 Accordingly, for the following discussion, the term “quasi-monoenergetic” neutron source will be used, and this term is meant to encompass any neutron source which is capable of generating a pulse of neutrons with the vast majority of the neutrons having one energy with a relatively narrow energy spread around it (e.g., $\Delta E/E < 0.5$). For the purposes of this disclosure, a low energy tail would be an acceptable
30 deviation from this, since those neutrons would not contaminate the measurement. As noted above, in one preferred form the pulse source may be the Dense Plasma Focus (“DPF”) generator used to demonstrate this method at Lawrence Livermore National Laboratory. The DPF generator is a kilojoule scale device which produces

a <50 ns neutron pulse, generates approximately 1×10^7 neutrons/pulse yield, has approximately a 200-liter volume, and weighs approximately 200kg, although it is expected that these dimensions can likely be reduced with minor modifications to about less than 80 liters in volume and 50 kg in total weight. The DPF is a Z-pinch like device which takes advantage of a plasma instability to create a high-intensity, short pulse (<100 ns Full Width Half Maximum) of neutrons with no dark current. Other possible pulse sources, for example and without limitation, may be a Z-pinch system or a laser-based neutron source.

[0023] With the present system and method, rather than relying on delayed neutrons for the identification, the system and method relies on detection of a neutron signal arriving prior to the signal induced by the un-scattered source neutrons. By using this early signal, the scattered signal does not affect the measurement and, thus, the identification is independent of moderating materials in the room, such as the floor, wall, or shielding placed over the fissionable material. Furthermore, typically short-pulse neutron generators, including DPF, Z-pinch or laser-based generators, do not exhibit “dark current”, which is a low level of neutrons emitted while the generator is off. This makes the early neutron pulses easier to differentiate. Finally, the short pulse interrogation signal approach does not remove the possibility of using active gamma spectroscopy or differential die-away, if other measurements are desired using the same interrogation source.

[0024] This technique provides a new way to detect fissionable material. The components include a neutron source and fast detectors that can be deployed around an object of interest. Referring to Figure 1, one example of a fast fissionable material detection system 10 (hereinafter simply “system 10”) is shown. The system 10 in this example includes a short pulse neutron generator 12 (hereinafter simply “pulse generator” 12) and a fast response detector 14. An electronic controller 15 may also be incorporated to control the fast response detector 14 and/or the pulse generator 12.

[0025] The pulse generator 12 in one preferred form may be the DPF generator as noted above, or alternatively the pulse generator 12 may comprise a Z-pinch generator or laser-based generator, or any other suitable form of short neutron pulse generator. For the purpose of the following discussion, it will be assumed that the pulse generator 12 is the DPF generator described above. Preferably, the pulse

generator 12 emits short, relatively low energy (e.g., <100 ns at full width half maximum (FWHM) neutrons <20MeV) pulses. In one specific implementation the pulse generator 12 may be a deuterium-based neutron source that emits neutrons near 2.5 MeV. Multiple pulses can be used to overcome limitations in signal strength from a single pulse, or a single sufficiently bright pulse could be used.

[0026] The fast response detector 14 may comprise a fast response neutron detector such as for example, but not limited to, Stilbene (an organic scintillator crystal) or Eljen 331 (a liquid scintillator commercially available from Eljen Technology of Sweetwater, TX). This detector may be run in a way (i.e., with a sufficiently high gain level) as to maximize the signal generated from single neutron observations to optimize this method. Running the detector 14 at this sufficiently high gain level will likely cause the detector signal to saturate when the main pulse from the unscattered source neutrons arrive. The rising edge of this saturated signal may be used as a timing fiducial for arrival of source neutrons. Multiple detectors may be used with different gain settings in order to properly allow for timing alignment among multiple neutron pulses or to maintain data integrity when a single intense pulse is used.

[0027] In operation, the pulse generator 12 is placed in the vicinity of an object of interest (e.g., typically within about 1-50 meters, or possibly even further). The pulse generator 12 emits neutrons below a given energy threshold, for example <10 MeV, and more preferably neutrons near 2.5 MeV. The fast response detector 14 is also placed in the vicinity of the object of interest (e.g., typically within about 1-50 meters, or possibly even further from the object of interest). The pulse generator 12 emits a short interrogation pulse 12a (<100 ns FWHM) of neutrons at mean energy preferably significantly below 10 MeV, which can interrogate an object of interest 16 as shown in Figure 1. Importantly, the pulse generator 12 does not emit a significant number of neutrons prior to the onset of this short interrogation pulse.

[0028] Once the interrogation pulse 12a is generated, the neutrons then impact the object of interest 16. If the object of interest 16 contains only non-fissionable material, the neutrons scatter from the object of interest 16, as indicated in highly simplified form by source neutrons 18 and form a characteristic die-away signal as measured by the fast response detector 14, the signal from which may be recorded by a sufficiently high-bandwidth digitizer or oscilloscope. If there is

fissionable material in the object of interest 16, the source neutrons 18 induce prompt fission events (i.e., create fission neutrons). These events have a characteristic energy spectrum which has a high energy tail up to approximately 20 MeV (maximum energy level), or possibly even higher. The higher energy neutrons, indicated in highly representative form in Figure 1 by reference number 20, have speeds significantly in excess of the lower energy neutrons from the pulse generator 12. Thus, the fast response detector 14 detects a small but significant number of these high energy neutrons 20 arriving before the source neutrons 18 are able to reach it. These “early arrival fission neutrons” are a characteristic signal of the presence of fissionable material in the object of interest 16 and thus provide a binary detection mechanism for the presence of fissionable materials. The fast response detector 14 may preferably be operated in a mode where multiple neutron events may be detected within a short time window. Several modes of operation can be used for the detectors. It may be desirable to put the fast response detector in line with the axis created by the source and object. This is the location with the most fission signal. However, depending on what source is used, it may be desirable to place the fast response detector at an angle (generally between 0 and 90° depending on the source geometry) relative to this axis. This allows for shielding of the detector from x-rays or gammas that some sources emit, and may arrive at the detector prior to the fission-induced neutrons, without shielding the direct line-of-sight from the object to the detector. Additionally, it may be desirable to use a collimator, such as optional collimator 13 shown in Figure 1, which forms a shaped structure used to shield radiation from certain lines of sight to the object of interest 16, to thus minimize the number of stray neutrons from the source pulse generator 12 that are emitted at angles such that they would not intersect the object of interest. It may be desirable to place the detector 14 in the shadow of the collimator 13. One advantageous mode of operation is the use of multiple detectors, set at different gains, so that some detectors can detect single pulses from the source while other detectors are set to avoid potential saturation. Secondary detectors can also be used to establish the timing of the neutron pulse and thus the time window in which to look for early arriving fission neutrons. In single pulse-counting mode, there are some fast detectors which can distinguish between photons and neutrons by pulse

shape. Such detectors may be used to eliminate “false positives” in the form of x-rays/gammas originating from the neutron source or object of interest.

[0029] Given the importance of precise timing to properly identify the fission neutrons, particularly when multiple source pulses are used, an electronic pulse generator (for example, a Stanford Research Systems DG 535) can be used to temporally align the source and detector. Given potential uncertainties in the exact timing of the source emission, this alignment can further be refined by analyzing the steep rise of the source neutron arrival (150a in Figure 3). Alternatively, if the source emits X-ray pulses coincident with the neutron pulse, these may also be used as a timing fiducial as well.

[0030] Figure 2 shows a graph 100 example modeling of a short pulse source incident on a fissionable and non-fissionable material (i.e., two unique scenarios). The portion of fission neutrons produced are indicated by portion 102 (i.e., when fissionable material is present in the object of interest 16). The source neutrons are indicated by number 104. Note the detection of the fission neutrons 102 begins at about the 105 ns mark (point 106 on the graph), which is well before the detection of the source neutrons 104 (beginning at about 130 ns, indicated by point 108 on the graph) which have not interacted with the fissionable material. It is notable that while fractional neutrons are predicted in the modeling, observed neutrons would be observed as binary impacts, so statistics may be built over numerous discharges.

[0031] Figure 3 further illustrates a waveform 150 in which portion 150a represents the detection of at least one fission neutron, while portion 150b represents the reception of the un-scattered neutrons at a point later in time. It is notable that the early event can be a single neutron impact, while the later peak represents the many overlapping arrivals of source neutrons, commonly referred to as “pile-up”.

[0032] This short pulse approach offers multiple benefits. The shortest path from the source to the fast response detector 14 determines the bound on the un-scattered detection timing. Since any neutron that is scattered in the room or goes straight to the detector without scattering will arrive after the high-energy fission neutrons, it will, thus, not contaminate the measurement being made by the fast response detector 14.

[0033] Furthermore, in contrast to die-away measurement techniques, the fast measurement for fission neutrons is not affected by other materials in the environment (e.g., container, room, etc.), for example wood, lead, steel, iron, plastic, vermiculite, dirt, etc., where the object of interest is located, or in which the object of interest is enclosed or encased. Advantageously, the short pulse used by the system 10 does not preclude the analyses from systems employing the die-away analysis, radiography, or gamma-ray spectroscopy.

[0034] One potential complication might include induced gamma rays from the object of interest, which will arrive at the fast response detector 14 before the source neutrons, and therefore could be misinterpreted as fast fission neutrons. Their number, however, is expected to be low, and they can be discriminated on sufficiently fast time scales. Additionally, the fast response detector 14 can be shielded such that it is not exposed to source gamma rays.

[0035] Referring briefly to Figure 4, a flowchart 100 is shown setting forth a plurality of operations that may be performed by the system 10 during its use. At operation 102, the pulse generator 12 generates an interrogation source pulse in the vicinity of the object of interest 16. At operation 104 the fast response detector 14 is used to detect the arrival of neutrons subsequent to generation of the source pulse. The fast response detector 14 may determine the presence of fission neutrons, as indicated at operation 106, based on the arrival time of the detected neutrons, with neutrons arriving within an initial predetermined time window that depends on the source neutron energy and the distance from the source to the detector (e.g., within about 130 ns of generation of the source pulse) indicating the presence of fission neutrons.

[0036] The system 10 and method of the present disclosure thus combines the use of a short pulse neutron source with the use of a fast response detector, in a unique and heretofore unexplored manner. The system 10 advantageously searches for a signal during a short, predetermined time, during which only fission neutrons would be received from an object of interest which has just been interrogated with source neutrons of a desired energy level and duration from a neutron pulse generator.

[0037] Focusing on this short duration time-window prior to the source neutron pulse, is an operation which has not been observed previously in practice. It

is possible that no previous attempts to exploit the detection of fast fission neutrons from an object of interest is due to the vast majority of commercial neutron sources being longer pulse ($> 1 \mu\text{s}$) accelerator-based sources. Such longer pulse, accelerator-based pulse sources cause this measurement for fast fission neutrons to be virtually indistinguishable in timing from neutrons generated by the source. Additionally, most commercially available generators exhibit "dark current" (a small number of neutrons being emitted during the "off" period), which makes the measurement of early arrival fission neutrons unfeasible, even if the small signal levels could be detected. Lower Technology Readiness Level ("TRL") and less rugged short-pulse neutron generators have largely remained outside of the active interrogation community, because they are typically not turn-key devices. Also, the much higher fluxes from these short-pulse generators may make it desirable to run centimeter-sized scintillator detectors in "current mode", in which multiple pulses from individual detection events may overlap in time. Running in current mode, however, has the disadvantage of lowering the observed signal level for individual pulses. This issue could be side-stepped by fielding a large array comprising smaller scintillators, sized to only receive a single pulse within a set time window. This issue can also be remedied in this approach by taking multiple pulses with the source at lower intensity and with higher gain on the detectors.

[0038] The foregoing description of the embodiments has been provided for purposes of illustration and description. It is not intended to be exhaustive or to limit the disclosure. Individual elements or features of a particular embodiment are generally not limited to that particular embodiment, but, where applicable, are interchangeable and can be used in a selected embodiment, even if not specifically shown or described. The same may also be varied in many ways. Such variations are not to be regarded as a departure from the disclosure, and all such modifications are intended to be included within the scope of the disclosure.

[0039] Example embodiments are provided so that this disclosure will be thorough, and will fully convey the scope to those who are skilled in the art. Numerous specific details are set forth such as examples of specific components, devices, and methods, to provide a thorough understanding of embodiments of the present disclosure. It will be apparent to those skilled in the art that specific details need not be employed, that example embodiments may be embodied in many

different forms and that neither should be construed to limit the scope of the disclosure. In some example embodiments, well-known processes, well-known device structures, and well-known technologies are not described in detail.

[0040] The terminology used herein is for the purpose of describing particular example embodiments only and is not intended to be limiting. As used herein, the singular forms “a,” “an,” and “the” may be intended to include the plural forms as well, unless the context clearly indicates otherwise. The terms “comprises,” “comprising,” “including,” and “having,” are inclusive and therefore specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof. The method steps, processes, and operations described herein are not to be construed as necessarily requiring their performance in the particular order discussed or illustrated, unless specifically identified as an order of performance. It is also to be understood that additional or alternative steps may be employed.

[0041] When an element or layer is referred to as being “on,” “engaged to,” “connected to,” or “coupled to” another element or layer, it may be directly on, engaged, connected or coupled to the other element or layer, or intervening elements or layers may be present. In contrast, when an element is referred to as being “directly on,” “directly engaged to,” “directly connected to,” or “directly coupled to” another element or layer, there may be no intervening elements or layers present. Other words used to describe the relationship between elements should be interpreted in a like fashion (e.g., “between” versus “directly between,” “adjacent” versus “directly adjacent,” etc.). As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0042] Although the terms first, second, third, etc. may be used herein to describe various elements, components, regions, layers and/or sections, these elements, components, regions, layers and/or sections should not be limited by these terms. These terms may be only used to distinguish one element, component, region, layer or section from another region, layer or section. Terms such as “first,” “second,” and other numerical terms when used herein do not imply a sequence or order unless clearly indicated by the context. Thus, a first element, component, region, layer or section discussed below could be termed a second element,

component, region, layer or section without departing from the teachings of the example embodiments.

[0043] Spatially relative terms, such as “inner,” “outer,” “beneath,” “below,” “lower,” “above,” “upper,” and the like, may be used herein for ease of description to describe one element or feature's relationship to another element(s) or feature(s) as illustrated in the figures. Spatially relative terms may be intended to encompass different orientations of the device in use or operation in addition to the orientation depicted in the figures. For example, if the device in the figures is turned over, elements described as “below” or “beneath” other elements or features would then be oriented “above” the other elements or features. Thus, the example term “below” can encompass both an orientation of above and below. The device may be otherwise oriented (rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein interpreted accordingly.

CLAIMS

What is claimed is:

1. A system for detecting fissionable materials, comprising:
5 a neutron pulse generator configured to generate multiple short pulses of neutrons, or a single pulse of sufficient intensity, in a vicinity of an object of interest;
the quasi-monoenergetic source pulse of neutrons including neutrons which each have a full width half maximum time duration of less than about 100 ns and a peak energy level no greater than about 20 MeV; and
10 a fast response detector able to detect single neutron events indicative of fission neutrons having been produced by the source pulse of neutrons interacting with fissionable material associated with the object of interest and arriving at the fast response detector within a predetermined time window immediately prior to arrival of the source neutron pulses.
15
2. The system of claim 1, wherein the mean energy level of the short pulses of neutrons comprises an energy level of about 2.5 MeV.
3. The system of claim 1, wherein the fast response detector comprises an
20 organic scintillator.
4. The system of claim 1, wherein the fast response detector comprises a liquid scintillator.
5. The system of claim 1, wherein the fast response detector comprises a
25 plurality of detectors having different gain settings.
6. The system of claim 5, wherein one of the plurality of detectors is configured to act as a secondary detector to establish a timing of the short duration
30 neutron pulses generated by the neutron pulse generator.
7. The system of claim 1, wherein the neutron pulse generator comprises at least one of:

a Z-pinch generator; or
a dense plasma focus generator.

5 8. The system of claim 1, wherein the neutron pulse generator comprises a laser-based generator.

10 9. The system of claim 1, wherein the fast response detector comprises a fast response detector configured to detect multiple neutron events with a given time window.

10. The system of claim 1, wherein the fast response detector is arranged along a direct line-of-sight with the neutron pulse generator.

15 11. The system of claim 1, wherein the fast response detector is arranged at an angle greater than 0 degrees up to 90 degrees, relative to a direct line-of-sight of the neutron pulse generator.

20 12. A system for detecting fissionable materials, comprising:
a neutron pulse generator configured to generate multiple short pulses of neutrons, or a single pulse of sufficient intensity, in a vicinity of an object of interest, and directed at a first side of the object of interest;

the multiple source pulses of neutrons having each having a full width half maximum time duration of less than about 100 ns; and

25 a fast response detector arranged remotely from the neutron pulse generator and facing a second side of the object of interest generally longitudinally along a line-of-sight with the neutron pulse generator, the fast response detector being time aligned with the generation of the multiple short pulses of neutrons, and further being configured to detect one or more fission neutrons produced by interaction of the source pulse of neutrons with fissionable material associated with the object of interest, and arriving at the fast response detector within a predetermined time
30 window immediately prior to the detection of the source neutron pulses by the fast response detector.

13. The system of claim 12, wherein the neutron pulses have a peak energy level no greater than about 20 MeV.

5 14. The system of claim 13, wherein the mean energy level of the short pulses of neutrons comprises an energy level of about 2.5 MeV.

15. The system of claim 12, wherein the fast response detector comprises an organic scintillator.

10 16. The system of claim 12, wherein the fast response detector comprises a liquid scintillator.

17. The system of claim 12, wherein the neutron pulse generator comprises at least one of:

15 a Z-pinch generator; or
a dense plasma focus generator.

18. The system of claim 12, wherein the neutron pulse generator comprises a laser-based generator.

20

19. The system of claim 12, wherein the fast response detector comprises a fast response detector configured to detect multiple neutron events with a given time window.

25 20. The system of claim 12, further comprising a collimator configured to shield radiation from the neutron pulse generator that diverges away from a line of sight path to the object of interest, to minimize the number of stray neutrons from the neutron pulse generator that are emitted at angles such that they would not intersect the object of interest.

30

21. A method for detecting a presence of a fissionable material associated with an object or interest, the method comprising:

generating multiple short pulses of quasi-monoenergetic source neutrons, or a single pulse of sufficient intensity, in a vicinity of the object of interest, wherein the source neutrons have a full width half maximum time duration of less than about 100 ns and a peak energy level no greater than about 20 MeV; and

using a fast response detector able to detect a single neutron event indicative of fission neutrons having been produced when the source neutrons interact with fissionable material associated with the object of interest, and wherein the fast response detector detects the single neutron event within a predetermined time window immediately prior to arrival of the source neutron pulses by the fast response detector.

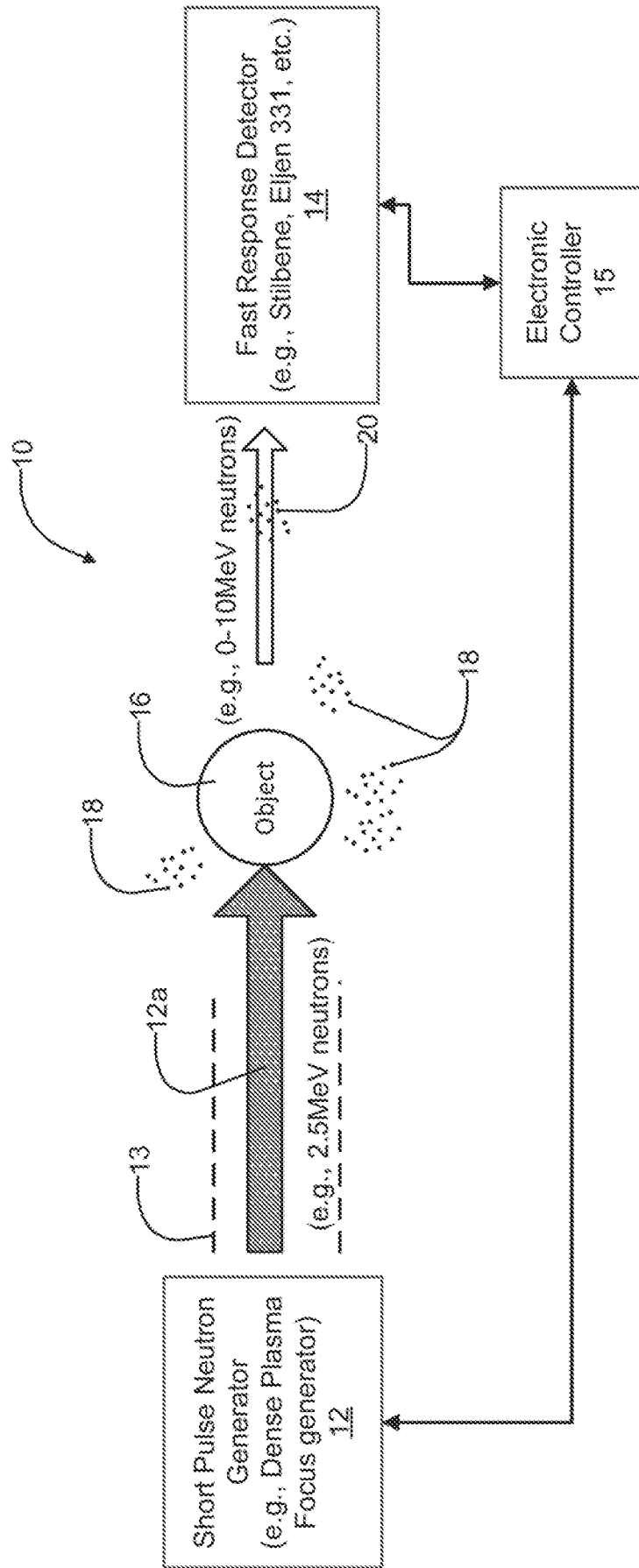
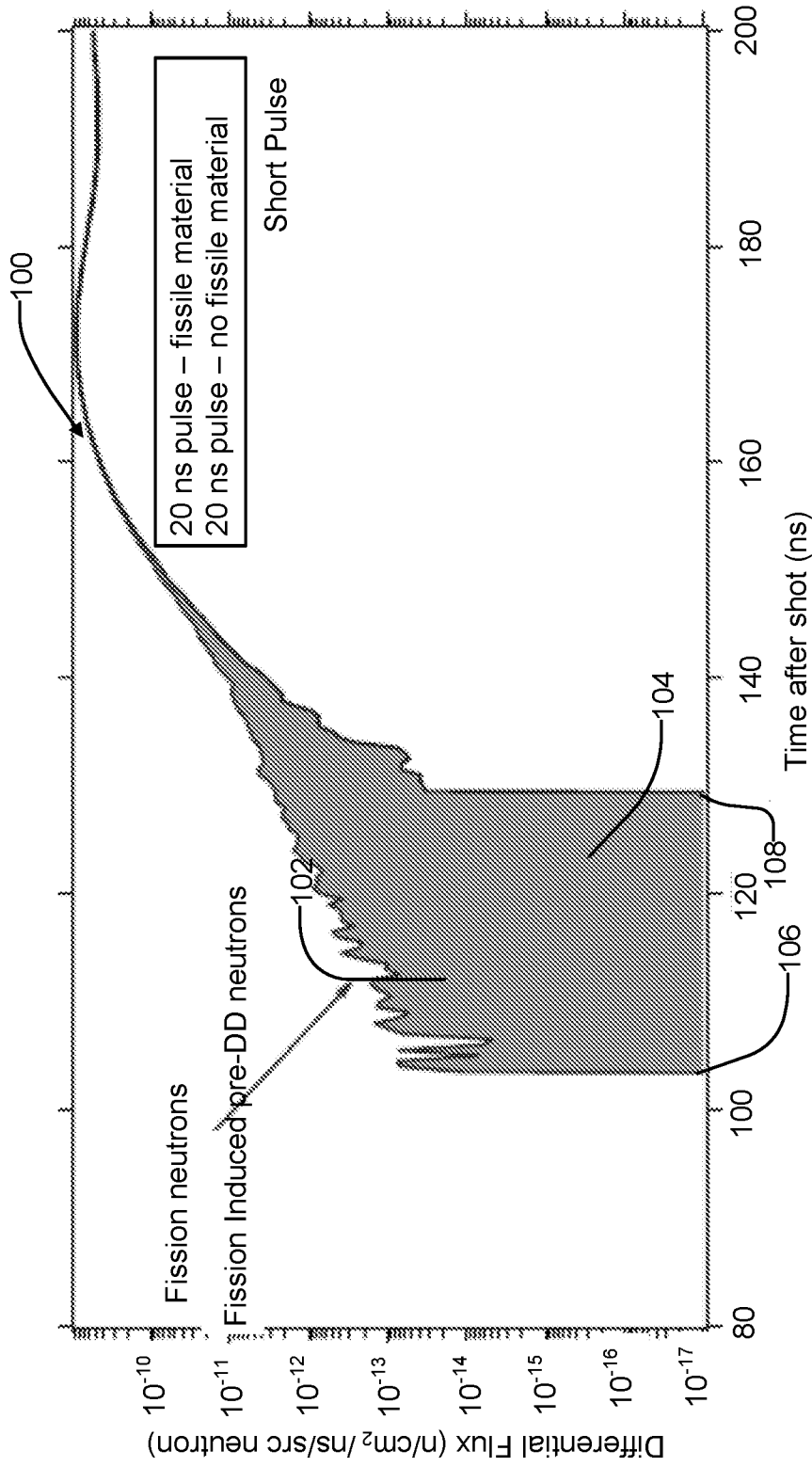


FIGURE 1



Monte Carlo N-particle (MCNP) Simulation of System Operation for Two Unique Scenarios

FIGURE 2

FIGURE 3

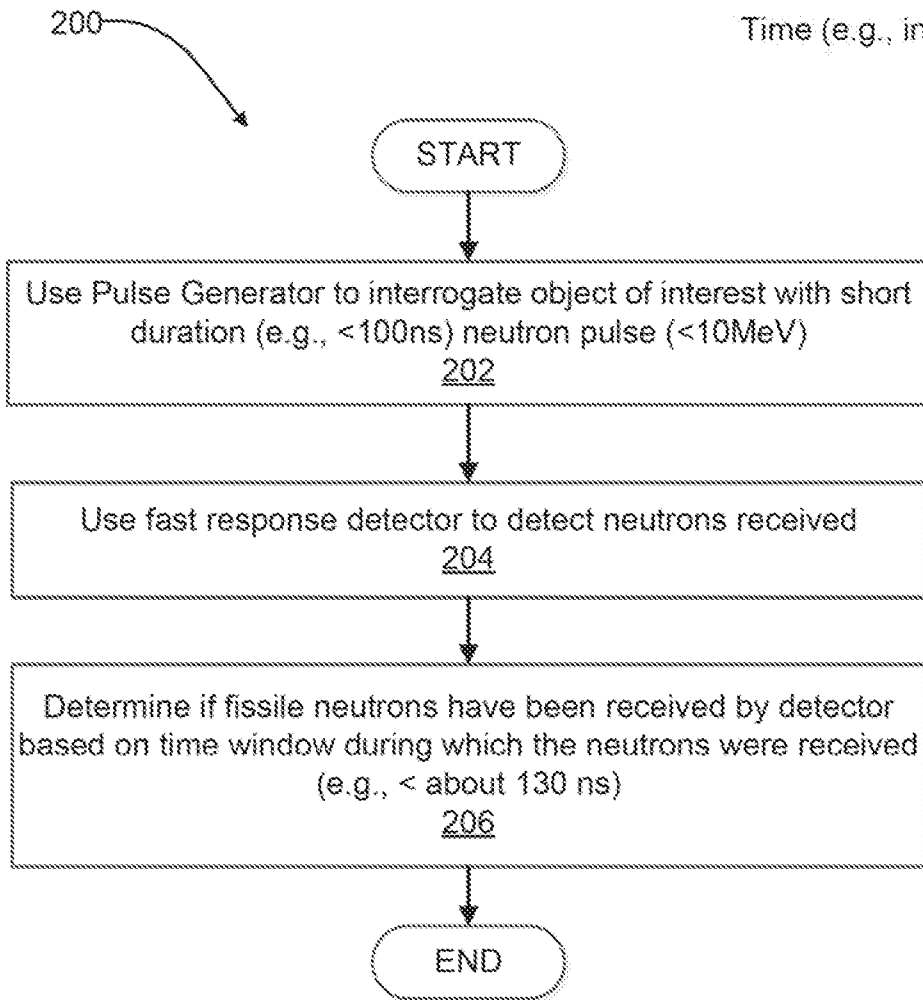
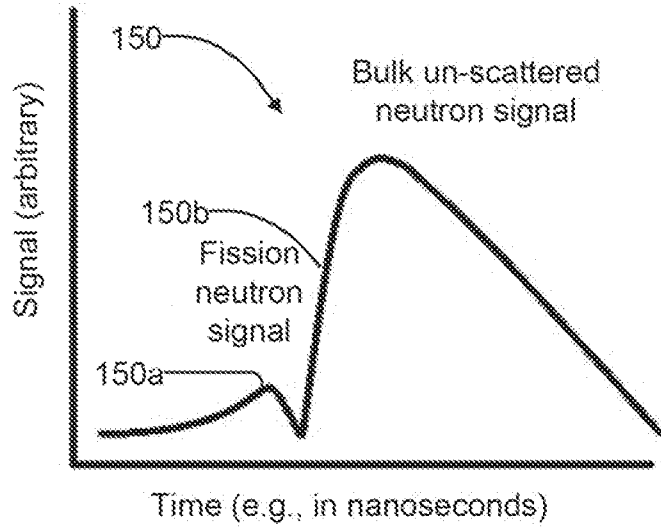


FIGURE 4

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2018/055050**A. CLASSIFICATION OF SUBJECT MATTER****G01V 5/00(2006.01)i, G01T 3/06(2006.01)i**

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHEDMinimum documentation searched (classification system followed by classification symbols)
G01V 5/00; G01N 23/00; G01T 3/00; G21C 7/08; G21G 1/00; G21G 1/08; G01T 3/06Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility modelsElectronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: fissionable material, neutron pulse generator, source pulses, fast response detector, scintillator**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2012-0314827 A1 (DIOSZEGI et al.) 13 December 2012 See paragraphs [0012]-[0054]; and claims 1, 17, 19, 21, 23.	1-11, 21
A		12-20
Y	US 2018-0188395 A1 (LAWRENCE LIVERMORE NATIONAL SECURITY, LLC.) 05 July 2018 See paragraph [0079]; and claims 4, 10.	1-11, 21
A	WO 2016-196799 A1 (BATTELLE ENERGY ALLIANCE, LLC. et al.) 08 December 2016 See claims 1-25; and figures 1-3.	1-21
A	US 2012-0155592 A1 (GOZANI et al.) 21 June 2012 See claims 1-24; and figures 1, 2A-2H, 3.	1-21
A	US 2009-0175401 A1 (BERTOZZI et al.) 09 July 2009 See claims 1-21.	1-21

 Further documents are listed in the continuation of Box C. See patent family annex.

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Date of the actual completion of the international search

21 May 2019 (21.05.2019)

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2018/055050

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