1 A Wearable Sensor Based on CLYC Scintillators

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5 Abstract

We have developed a wearable radiation sensor using Cs₂LiYCl₆:Ce (CLYC) for simultaneous gamma-ray and neutron detection. The system includes two $\phi 2.5 \times 2.5 \text{ cm}^3$ crystals coupled to small, metal-body photomultiplier tubes. A custom, low-power electronics base digitizes the output signal at three time points and enables both pulse height and pulse shape discrimination of gamma rays and neutrons. The total counts, anomaly detection metrics, and identified isotopes are displayed on a small screen. Users may leave the device in unattended mode to collect long-dwell energy spectra. The system stores up to 18 hours of one-second data, including energy spectra, and may transfer the data to a remote computer via a wired or wireless connection. The prototype is $18 \times 13 \times 7.5 \text{ cm}^3$, weighs 1.3 kg, not including the protective pouch, and runs on six AA alkaline batteries for 29 hours with the wireless link active, or 41 hours with the wireless link disabled. In this paper, we summarize the system design and present characterization results from the detector modules. The energy resolution is about 6.5% full width at half maximum at 662 keV due to the small photomultiplier tube selected, and the linearity and pulse shape discrimination performance are very good.

6 *Keywords:* CLYC, wearable, low power, unattended sensor, gamma ray, neutron,
7 anomaly detection, radioisotope identification

8 1. Introduction

9 Many personal radiation detectors lack the sensitivity and specificity to character-
10 ize threats or are operationally burdensome (e.g., heavy or large). Other drawbacks
11 include relatively short (8-hour) operating lifetimes and high false alarm rates. At Pa-
12 cific Northwest National Laboratory (PNNL), we have developed technology to alleviate
13 these problems. These solutions combine new detector materials with low-power elec-
14 tronics and real-time analysis algorithms for teasing threat signatures from noisy data.
15 One promising material is Cs₂LiYCl₆:Ce (CLYC). This elpasolite scintillator combines

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16 medium gamma-ray energy resolution (3.9% full width at half maximum (FWHM) at
 17 662 keV) with the ability to detect thermal neutrons via ${}^6\text{Li}(\text{n}, \alpha){}^3\text{H}$ neutron capture [1].
 18 Neutron capture events produce a peak in the energy spectrum around 3.2 MeV electron
 19 equivalent (MeVee), which is 67% of the 4.8 MeV released from the neutron capture re-
 20 action. The primary emissions, due to self-trapped excitation and Ce^{3+} luminescence,
 21 have a characteristic decay component of $4.3 \pm 0.1 \mu\text{s}$, with additional components around
 22 400 ns, and wavelengths ranging from 350 to 450 nm. Gamma interactions also produce
 23 core-to-valence luminescence with a fast decay time of $2 \pm 1 \text{ ns}$ and wavelengths ranging
 24 from 250 to 350 nm [2, 3]. This effect allows the use of pulse shape discrimination (PSD);
 25 however, the PSD performance degrades at higher temperatures [4, 5]. Recent work has
 26 also demonstrated fast neutron detection and spectroscopy via the ${}^{35}\text{Cl}(\text{n}, \text{p}){}^{35}\text{S}$ reac-
 27 tion [6]. The efficiency for fast neutrons is quite low compared with thermal neutrons,
 28 and we only focused on discriminating thermal neutrons in this project.

29 A handful of portable, combined neutron-gamma systems have been created recently.
 30 One system, circa 2004, was based on $\text{Li:I}(\text{Eu})$, which has roughly 8% FWHM at 662 keV
 31 and good thermal neutron efficiency, but no PSD capability [7]. More recently, two sys-
 32 tems based on CLYC have been developed by Los Alamos National Laboratory (LANL)
 33 and collaborators. The first is a hand-held, power-over-Ethernet device called the Com-
 34 pact Advanced Readout Electronics for Elpasolites (CAREE) [8]. This system utilizes a
 35 PSD-capable ASIC, consumes 2.28 W on average, achieves count rates up to 20 kHz, and
 36 supports various detector sizes. The second, the Advanced Radiation Monitoring De-
 37 vice (ARMD), is battery powered, utilizes the same ASIC, draws approximately 3.6 W,
 38 has a similar count rate capability as CAREE, and incorporates four CLYC detectors
 39 for greater sensitivity and directionality capability [9]. At least two commercial devices
 40 now incorporate CLYC. One is the RIIDEyeTM X series made by Thermo Scientific
 41 (www.thermoscientific.com). It uses a $\phi 1.8 \times 3.4 \text{ cm}^3$ crystal in the handle of a handheld
 42 device for neutron detection only and a larger NaI:Tl or $\text{LaBr}_3\text{:Ce}$ crystal for gamma de-
 43 tection. Another recent commercial device is the F500 made by Target Systemelektronik
 44 (<http://target-sg.com>), which optionally includes a single $\phi 5.1 \times 5.1 \text{ cm}^3$ CLYC detector
 45 for combined neutron and gamma detection.

46 The use of the same material for detecting gamma rays and neutrons has obvious ben-
 47 efits for reducing the size and weight of personal radiation detectors. However, low-power
 48 electronics and computationally efficient analysis algorithms are also key to maximizing
 49 battery life. PNNL has developed a number of autonomous radiation detection systems,
 50 known as unattended sensors, that feature advances in both areas. A first-generation
 51 unattended sensor, completed in 2009, contained two standard NaI:Tl $5 \times 10 \text{ cm} \times 40.6 \text{ cm}^3$
 52 detectors for gamma-ray spectroscopy and eight ${}^3\text{He}$ proportional counters for thermal
 53 neutron detection [10]. Each gamma detector had a count rate capability of 10 kcps.
 54 Notable features of this system included the low-power electronics for detector readout
 55 and bias, which were limited in count rate but consumed an order of magnitude lower
 56 power than commercial systems. The unattended sensor also implemented a computa-
 57 tionally efficient algorithm developed in earlier efforts to classify energy spectra as either
 58 benign or anomalous. This energy windowing technique, known as N-SCRAD, allows
 59 for anomaly detection at much lower count rates than possible with traditional isotope
 60 identification methods [11].

61 A next-generation unattended sensor, completed in 2012, integrated the gamma-ray
 62 and neutron detection capabilities into one volume using CLYC [12, 13]. The unattended

63 sensor contained sixteen $\phi 2.5 \times 2.5 \text{ cm}^3$ CLYC detectors, each read out by a high quantum
 64 efficiency Hamamatsu R9420-100 super bi-alkali photomultiplier tube (PMT) and custom
 65 low-power electronics. Although the total active volume was much lower than the original
 66 system, the neutron detection efficiency was comparable to much larger first-generation
 67 unattended sensor, which used ^3He proportional tubes. The next-generation unattended
 68 sensor also featured a new algorithm, known as quick ID (QID), for performing isotope
 69 identification on computationally limited hardware. The combination of N-SCRAD and
 70 QID permits positive identification of known sources and anomaly detection of unknown,
 71 weak, or shielded sources. The total count rate limitation of the system was around
 72 3000 cps, which was a tradeoff in low-power electronics design that enabled month-long
 73 operation on battery power.

74 2. Design

75 2.1. Overview

76 We have developed a wearable radiation sensor for detecting and identifying illicit
 77 radioactive material, dubbed the Low Profile Sensor (LPS). The LPS may be worn on
 78 the chest for real-time alarm notification, or used as an unattended sensor. An overall
 79 goal of this project was to assess how CLYC performs as a material in a wearable, low-
 80 power device. Potential applications of the system include impromptu portal monitoring
 81 and long-dwell source characterization. Furthermore, this system is designed for both
 82 specialist and non-specialist use. The specialist can monitor anomaly metrics and isotope
 83 identification results. The non-specialist can perform surveys, wirelessly transmit data,
 84 and wait for feedback from experts. In brief, the LPS offers the following capabilities:

- 85 • Combined gamma-ray and neutron detection
- 86 • Greater neutron sensitivity than ^3He proportional counters by volume
- 87 • Standard gross count and sigma-over-background alarms
- 88 • Anomaly detection algorithm (N-SCRAD) for enhanced sensitivity to illicit materi-
 89 als and reduced false alarms from naturally occurring radioactive material (NORM)
- 90 • Isotope identification algorithm (QID) with 20 template materials
- 91 • Visual and audible alarms
- 92 • Backlit liquid crystal display (LCD)
- 93 • USB and Wi-Fi connections
- 94 • Data transfer in ANSI N42.42 format or plain text

95 2.2. Detectors

96 The sensor contains two $\phi 2.5 \times 2.5 \text{ cm}^3$ CLYC crystals manufactured by Radiation
97 Monitoring Devices, Inc. These detectors were the largest size available during the design
98 phase; $\phi 7.6 \times 7.6 \text{ cm}^3$ crystals are now offered. We chose two crystals to increase the
99 detection efficiency and provide backup functionality in case one of the components fails.
100 As delivered, the crystals are wrapped with Teflon tape and packaged inside a sealed
101 aluminum housing with a fused silica quartz window, as CLYC is hygroscopic. Event-
102 by-event data from the detectors are summed if they occur within a small time window,
103 thereby moving downscattered events to the photopeak. The crystals are placed relatively
104 close together to maximize this effect, which was studied with MCNP5 V1.60 [14].

105 2.3. Mechanical Design

106 Figure 1 illustrates a cross-section rendering of the LPS without its protective pouch.
107 The housing consists of several compartments: an inner housing for the detector and
108 PMT, and separate chambers for the batteries and processing electronics. The detector,
109 batteries, and circuit boards are placed inside a plastic enclosure with overall dimensions
110 of $13 \times 7.5 \times 18 \text{ cm}^3$. The total mass of these components is 1.3 kg. The enclosure fits inside
111 a padded pouch that can be attached to the body via Modular Lightweight Load-carrying
112 Equipment (MOLLE) straps or placed inside a bag.

113 Each CLYC detector is coupled to a Hamamatsu ultra bi-alkali R11265-200 PMT
114 via a 1.5 mm thick Eljen Technology EJ-560 optical interface pad. A small amount of
115 Saint Gobain Crystals BC-630 silicon grease is used on both sides of the pad. These
116 pads provide excellent optical coupling that will not leak out over time like optical grease
117 alone. They also offer some protection for the PMT/detector interface against mechanical
118 shocks. The PMT is a square, metallic body, “ultra bi-alkali” type with overall dimen-
119 sions of $2.6 \times 2.6 \times 2.2 \text{ cm}^3$. The metal body provides much greater mechanical robustness
120 and magnetic shielding compared with typical glass PMTs. No reflective material was
121 wrapped around the edges of the PMT-crystal interface as the enclosure tolerances were
122 tight and tests indicated that Teflon wrapping did not impact the energy resolution per-
123 formance. These components are packed into a light-tight inner enclosure and surrounded
124 by vacuum insulation panels on five sides (all but the top) to protect against thermal
125 shock.

126 A small calibration source is placed into a pocket on the inner enclosure between
127 the detectors to provide two gamma ray peaks for continuous energy calibration. The
128 calibration source, manufactured by Spectrum Technologies, LLC, consists of 10 nCi
129 $\pm 20\%$ of ^{22}Na deposited into a small hole on a polycarbonate rod, which is then sealed
130 with epoxy and a threaded plug.

131 2.4. Electronics

132 The LPS features a low-power PMT base to generate the voltage biases and read out
133 the signal. A Cockcroft-Walton diode-capacitor multiplier produces negative biases for
134 the cathode and dynodes, allowing the anode signal to be coupled directly to the readout
135 circuit. Special care is taken to shield the sensitive anode signal from the large signals on
136 the diode-capacitor multiplier. In fact, the anode signal is routed onto a small coaxial
137 cable which connects to the outermost circuit board on the stack.

Figure 1: A cross-sectional view through a SolidWorksTM model of the LPS.

138 A diagram of the readout circuit and its basic operation appears in Figure 2. To
 139 cleanly separate gamma-ray and neutron interactions, the base supports both pulse am-
 140 plitude measurements and pulse shape discrimination (PSD). The anode current i_P from
 141 the coaxial cable is integrated onto capacitor C , with continuous reset provided by resis-
 142 tor R . The analog-to-digital converter (ADC) samples the integrated voltage at 115 ns,
 143 750 ns, and 6.0 μ s after the initial trigger. These sample times were chosen based on
 144 the optimizations reported in [15], and are the same in all LPS units. The last sample
 145 v_3 corresponds to the primary channel number, which is converted to the deposited en-
 146 ergy. The ratio $(v_1 - v_2)/v_3$ defines a PSD statistic. This procedure is very similar to
 147 the two-window technique implemented on the ASIC used in the LANL systems. Sub-
 148 sequent firmware uses fixed cutoffs on the pulse height and pulse shape to classify an
 149 event as a neutron. Although the gain changes with respect to temperature, this tech-
 150 nique has proven satisfactory up to 50 °C. While PSD is possible with CLYC at higher
 151 temperatures, the PSD performance decreases with increasing temperature [16, 17].

152 The RC time constant of the readout circuit is rather high, being nominally 6.2 μ s.
 153 We found that a large time constant was necessary to collect residual charge from the
 154 PMT, due at least in part to the presence of long-lived decay components in the CLYC
 155 scintillator. Leakage pathways through the PMT or high voltage boards, exacerbated
 156 by the small size of the module, may also have contributed to this effect. Because the
 157 readout circuit does not contain a shaping amplifier, both to save power and to preserve
 158 PSD information, the system has a dead time of about 30 μ s, limiting the count rate to
 159 roughly 10 kHz. Subsequent buffering and processing limits the effective count rate to
 160 about 4 kHz, after which point the system indicates an error condition. We felt that these
 161 tradeoffs were reasonable considering the small size of the detectors and the emphasis on

Figure 2: Readout circuit and diagram of pulse processing showing information required for PSD (not to scale).

low power consumption.

Data from each PMT base is channeled to a custom processing board. This board contains a Microsemi SmartFusion2 system-on-chip (SoC) field programmable gate array (FPGA) to analyze data and control the system operation. Other components on the board include a small LCD screen, USB interface, and Wi-Fi module for transferring data remotely.

Six alkaline AA batteries in an accessible compartment supply power to the system. We chose standard AA batteries over lithium cells because they are ubiquitous, easily obtainable, and do not require special shipping or handling procedures. The batteries are placed inside a holder that slides between the top and bottom compartments of the outer enclosure. Also inside the battery compartment is a microUSB connector for transferring data from the LPS to a computer.

2.5. Firmware and Algorithms

The readout and energy calibration are performed independently for each channel. Downstream firmware sums the energies of coincident events together in an effort to improve the peak efficiency at higher energies. After acquiring event data, the firmware performs energy calibration using the measured locations of the 511 and 1274 keV peaks from the ^{22}Na calibration source. Normally, a two-parameter fit is performed every ten minutes, or longer if an alarm occurs during the interval. To reduce the system warm-up time, an initial one-parameter fit is performed on the 511 keV peak alone within one minute after power-on. The calibration technique filters the measured spectrum with a zero-area square wave to suppress non-peak spectral features and then finds the maximum value near the expected location. The firmware applies the fit parameters to each subsequent gamma-ray event. Coincident gamma-ray events in both detectors within a 10 μs window are summed together to improve the detection efficiency at high energies. Preliminary modeling studies indicated that summing multi-crystal events increases the peak efficiency of the 662 keV photons by nearly 10% relative. Essentially, this operation moves counts from the continuum to the peak. This approach is susceptible to accidental

coincidences, which show up as sum peaks in the energy spectrum. The tradeoff between peak efficiency boost from crystal event summing and artifacts from summing was not studied in this effort.

The LPS integrates events over a three-second interval and computes a set of alarm metrics each second. These alarm metrics include total counts, sigma over background, and the N-SCRAD anomaly detection algorithm developed in previous work. A dead time correction is applied to compensate for skipped events and for the readout time of the PMT base. Algorithms run in real time to allow rapid detection of potential threat sources.

The N-SCRAD anomaly detection algorithm classifies an energy spectrum as either consistent or inconsistent with prior measured background and a predefined set of “nuisance” sources such as NORM [11]. The algorithm generally performs better than gross count techniques in the presence of variable backgrounds (such as those encountered by wearable detectors) and nuisance sources. Fundamentally, N-SCRAD is an energy windowing technique that compares the ratios of counts in two windows to expected values. Any contributions from nuisance sources are projected out. The residuals are then combined via a standard distance metric and scaled so that a value of 1.0 indicates an alarm. The process is then repeated for other sets of energy windows, taking the maximum scaled result as the final alarm metric. The LPS presently uses four sets of windows for N-SCRAD. Each set contains between four and seven windows. Window boundaries may be sensitive due to being optimized on particular targets, so we do not list them here. The instrument displays the maximum result but saves all four values to memory. Specific window boundaries are optimized to improve sensitivity to special nuclear material and other sources of concern. However, the algorithm still retains sensitivity to other sources. The optimization process is performed offline using simulated source spectra, and involves testing a large number of windows and picking the combination that detects the selected sources most successfully. For the set of nuisance sources, the LPS presently uses ^{40}K as the single nuisance source. Other NORM components such as ^{238}U and ^{232}Th do not present many distinguishing features in the most sensitive energy range of the instrument, which is up to roughly 1.5 MeV.

A simple isotope identification algorithm known as QID (“quick ID”) further classifies anomalous spectra. Based on earlier algorithms for handheld radioisotope identifiers [18], QID filters the energy spectrum with a zero-area square wave to isolate the peak information, and then performs an iterative least-squares fit against a library of common sources. When the total counts, sigma over background, or N-SCRAD algorithms trigger an alarm condition, the LPS collects energy spectra for a configurable integration time and then executes QID. QID performs an iterative least-square fit against template isotopes in a library, successively discarding isotopes that provide insignificant contributions to the total. Prior to the least-squares fit, however, both the measured spectra and the templates pass through a square wave convolute filter. This filter attenuates all features in the spectrum except the photopeaks, allowing more reliable identification with unknown shielding configurations. The library presently contains 21 signatures, ranging from medical sources to SNM. For simplicity, the instrument collects a new set of energy spectra prior to each identification.

234 3. Assembly

235 The detector assemblies are installed inside a light-tight inner enclosure, which con-
 236 sists of two halves that slide together. Figure 3 gives an outline of this process. First,
 237 each PMT is soldered to a circuit board which routes the PMT leads to an on board
 238 multi-pin connector. Second, these interface boards are epoxied into one half of the en-
 239 closure to form a light-tight seal around the connector. The epoxy is kept well away from
 240 the connector pins to prevent high voltage conduction. Third, a silicone optical interface
 241 pad is placed on top of each PMT, using a minimal amount of optical coupling grease to
 242 hold the pad in place. Fourth, the two CLYC crystals are placed on top of the respective
 243 pads, and small metal springs are placed on top of the detectors to provide compression.
 244 Finally, the other half of the inner enclosure is slid onto the assembly and fastened into
 245 place. All the above steps were performed in a dimly-lit room to prevent damage to the
 246 PMT photocathodes.

Figure 3: Photographs of the LPS components and assembly for the Delrin® enclosure.

247 Three LPS units were constructed. The first was made with traditional subtractive
 248 machining techniques out of black Delrin® acetal homopolymer . The other two were
 249 made via additive manufacturing (3D printing) by Proto Labs, Inc. (www.protolabs.com),
 250 which involved a two-step process. First, base parts of ceramic-filled composite were made
 251 via stereolithography. Second, these parts were then electroform-plated with a thin nickel

(a)

(b)

Figure 4: (a) Photograph of an assembled LPS (3D-printed version) with the LCD screen showing a gamma alarm indication. (b) Photograph of an LPS in its protective pouch within a transport case..

alloy layer (SLArmor™) to provide structural strength and to ensure optical opacity of the case for the PMTs. The LPS fits within a nylon pouch (Tactical Taylor, Inc., Lakewood, WA) with a flip-open top and modular straps. A foam insert for the pouch was crafted by Bauer Cases (Vancouver, WA). The carrying pouch had 1.3 cm thick foam walls of medium-density Stratocell®170 polyethylene foam (Sealed Air Corp.) to provide cushioning for drops and impacts.

4. Characterization

4.1. Gamma Ray Detection

Here we present the preliminary characterization results at the detector and system level for LPS unit #2, which incorporates a 3D-printed enclosure. The two individual packaged CLYC crystals in this prototype unit were characterized at 4.6% and 4.7% FWHM at 662 keV by the manufacturer using a Hamamatsu R6233-100 super bi-alkali PMT and benchtop electronics. Coupling the packaged crystals to the smaller R11265-200 PMT and low-power electronics increased these values to 6.2% and 5.8%, respectively. We found that most of the performance degradation was due to the small PMT: using benchtop electronics and high voltage supplies only improved the performance slightly. The resolution results are also consistent with the ARMD, which used R11265-100 super bi-alkali PMTs, which have the same size and slightly less quantum efficiency than

the R11265-200 [9]. The CAREE system by contrast used a 2 in.-diameter PMT and achieved 4.9-5.6% resolution [8].

The low-energy threshold of the LPS is excellent, with the 32-keV X-rays from ^{137}Cs prominently visible in the energy spectrum. The detector assemblies have very good linearity as well, with peaks falling within ± 5 keV from 32 keV to 2614 keV. The correlation coefficients of the measured peak locations with respect to a linear fit are greater than or equal to 0.99997 in all cases. The dynamic range of the system extends from 20 keV to roughly 3500 keV (above the neutron peak).

Figure 5 illustrates a typical gamma-ray spectrum from one unit, taken for approximately 2.5 hours with and without the ^{22}Na calibration source. The background, background plus calibration source, and calibration source spectra are plotted. The ^{40}K background peak at 1461 keV is not visible in the background-only spectrum. Above the ^{22}Na 1274 keV peak are sum peaks near 1474 (1274 keV plus backscattered photons) and 1785 keV (511 plus 1274 keV).

Figure 5: Gamma ray spectrum from LPS unit #2 with ^{22}Na calibration source. The 511 and 1274 keV peaks from ^{22}Na are distinct, as is a small sum peak at 1785 keV. The measurements were made for 9084 s and the spectra are combined from both crystals.

Table 1 gives the measured energy resolution and intrinsic peak efficiency of LPS unit #2. The latter is the number of peak counts divided by the number of incident photons of that peak energy. The number of peak counts is determined by fitting the peak with a Gaussian function and subtracting a linear baseline. The outer compartment of the LPS

Table 1: Intrinsic peak efficiency and energy resolution measurements for LPS unit #2.

Energy (keV)	Intrinsic peak efficiency		FWHM (%)	
	Module A	Module B	Module A	Module B
59.5	0.66	0.68	25.0	23.0
81.0	0.80	0.80	20.9	18.9
356.0	0.18	0.20	8.37	7.96
661.7	0.08	0.08	7.05	6.47
1173.2	0.03	0.03	6.21	5.78

was temporarily removed for these measurements. The inner compartment was placed on polystyrene foam to reduce scattering. Gamma-ray spectra were recorded for each of the two CLYC detectors in the instrument. Sources were placed into a small foam jig that aligned the source with the center of the unit and placed 25 cm from the face of the crystals. The peak intrinsic efficiency values at 662 keV are about an order of magnitude smaller than the values at low energies. Larger detector sizes would clearly help improve the peak efficiency, but were not commercially available when the LPS was designed. Note that the attenuation of gamma rays by the housing was not included, which accounts for the lower intrinsic efficiency at 59.5 keV than 81.0 keV.

4.2. Neutron Ray Detection and PSD

Figure 6 plots a two-dimensional histogram of the PSD statistic versus the channel number from one detector module. The system ran for 97 minutes with a small ^{137}Cs source and a ^{252}Cf neutron source several meters away. The calibration source was not installed. Neutron events are clearly separable from the gamma-ray background in the plot. We used a common PSD figure of merit (FOM) [19], which is the distance between the gamma and neutron peaks divided by the sum of the FWHM of the peaks at some given energy (pulse height) cut. A derivation of the conversion from FOM to GRR is given in Appendix A. The measured, estimated FOM of 2.70 corresponds to a gamma rejection ratio (GRR) better than 10^{-7} (e.g., fewer than one in ten million gamma rays will be mistaken as neutrons assuming both peak shapes are Gaussian). This result is not as high as the FOM of 4.55 reported for the ASIC used in the LANL system [15], but still sufficient for very good PSD performance. LPS unit #1 had one crystal give a lower FOM of 1.96, and this corresponds to a GRR close to 10^{-6} . All other crystals had FOMs better than 2.40.

Two configurations were used for neutron efficiency measurements. One setup represented the system being worn over a human torso; the other setup represented the system left behind. Two poly(methyl methacrylate) (PMMA) slabs were used to represent a human torso. The configuration, shown in Figure 7, was two stacked $30.5 \times 30.5 \times 15.2 \text{ cm}^3$, similar to the phantoms described in American National Standards Institute (ANSI) standard N42.53 and the Domestic Nuclear Detection Office Technical Capability Standard for Backpack Based Radiation Detection Systems. A ^{252}Cf source in a thin polyethylene pig was placed 25 cm from the fully assembled LPS unit inside its protective pouch. A summary of the neutron detection performance in the worn and unworn configurations appears in Table 2. Wearing the unit on the chest improves the detection efficiency by

(a)

(b)

Figure 6: (a) Two-dimensional PSD histogram from a typical, single detector module with ^{137}Cs calibration source and ^{252}Cf neutron source. The box shows the region used to compute the PSD figure of merit. Note that the color bar is on a log scale. (b) Data projected onto the Y-axis of (a) showing neutron- and gamma-event peaks and Gaussian fits. The FOM is 2.70.

more than a factor of two. Placing the unit next to an external moderator such as a water bottle or concrete barrier will improve the neutron detection performance when the unit is not being worn.

Figure 7: Absolute neutron detection efficiency measurement setup in unworn configuration (left) and worn configuration (right)

Table 2: Neutron efficiency measurements for LPS Unit #2 in worn and unworn configurations. The last column refers to the number of ng of ^{252}Cf .

Configuration	PSD figure of merit		Abs. efficiency $\times 10^{-5}$ Total	cps/ng at 25 cm Total
	Module A	Module B		
Worn	2.74	2.70	21.9	0.51
Unworn	2.64	2.68	7.74	0.18

4.3. Temperature Shocks

We also wished to evaluate whether the LPS could withstand significant temperature changes. Accordingly, one of the prototype units (unit #1) was subjected to the following tests:

- Cold-to-ambient: Placed LPS in a refrigerator overnight at approximately 5°C , then taken out of the refrigerator to a 20°C lab, with temperature probe recording internal temperature.

- Hot-to-ambient: Placed LPS in heated insulated box overnight at approximately 45°C , then taken out of box to 20°C lab with temperature probe recording internal temperature.

A rule of thumb with scintillator detectors is to limit the temperature gradient to $5^{\circ}\text{C}/\text{hour}$, or $10^{\circ}\text{C}/\text{hour}$ in the worst case. Analysis of the test results revealed that an external temperature step of 20°C will limit the internal temperature gradient to

5° C/hour. Similarly, an external temperature step of 40° C will limit the internal temperature gradient to 10° C/hour. Thus, the LPS should withstand the scenario of moving from an air-conditioned vehicle at 20° C to a hot desert environment at 40° C. Moving from a heated vehicle at 25° C to a winter environment at -15° C does approach the worst-case limit. The 511 keV peak from the ²²Na calibration source experienced a gain shift of ±1.5% in the uncalibrated spectrum during the temperature tests. The LPS remained functional with no problems noted with the energy calibration routine. The PSD was measured during these temperature tests with the ²²Na source and a ²⁵²Cf source. For the hot-to-ambient test, the FOM increased from 2.1 to 2.6 over eight hours starting at 45° C and ending at 26.5° C. For the cold-to-ambient test, the FOM correspondingly decreased by 0.5 from 3.6 to 3.1 over four hours starting at 5° C and ending at 20° C. These tests indicate that the PSD FOM remains adequate over the temperature range of interest and that the thermal insulation keeps the temperature gradient below 5° C/hour over these changes. These results were for the second CLYC crystal in unit #1; the first crystal in this unit had lower FOMs (1.96 at room temperature) than all of the other five crystals. The FOM for this anomalous crystal also changed by roughly 0.5 for the temperature tests.

4.4. Battery Lifetime

The aggressive optimizations performed to reduce the power consumption permit the LPS to operate from battery power for extended intervals. We found that the LPS runs continuously for 29 hours from a fresh set of standard AA alkaline batteries at room temperature with the Wi-Fi enabled and transmitting data every second. Turning off the Wi-Fi increases the operating time to 41 hours, allowing the LPS to collect long-dwell measurements as an unattended sensor. The current on-board storage is large enough for 18 hours of continuous spectra acquisition. This is something that could be easily addressed in a new development spiral. Data compression schemes could help here, but these add computational cost and were undesired. Additional storage features such as removable memory cards could also enable longer-dwell unattended applications.

Table 3 breaks down the power consumption by component, assuming a typical use scenario where the LCD backlight and Wi-Fi are only turned on 1% of the time. The total power is 471 mW—7.6 times lower than the LANL battery-operated system (ARMD [9]). The measured power consumption of 64 mW per PMT, including the high voltage generator and readout circuit, is well below commercial systems.

4.5. Summary

Table 4 lists the system specifications developed as a result of the preliminary characterization measurements and functional testing.

5. Conclusion

This article has described a low-profile sensor that uses CLYC scintillators to combine gamma-ray identification and neutron detection in the same volume. The system power consumption of less than 500 mW enables the dual use of the system as both a wearable detector and unattended sensor. However, the count rate capability is limited to about 4 kHz due to the tradeoffs made in the design. Above that count rate an error mode

Table 3: Approximate power consumption by component.

Component	Power (mW)
PMT bases (two)	128
Processor + FPGA	216
SDRAM	35
LCD	7
Backlight (1% duty)	5
Wi-Fi (1% duty)	2
Voltage converters	78
Total	471

is triggered and displayed as the readout electronics cannot reliably process events. The LPS is thus not well-suited for use as a dose meter, and has limited ability to discriminate neutrons from gamma rays in significant gamma fields. The latter is a common limitation of all dual-particle, single-readout systems. However, applications which foremost require portability and power duration will likely benefit from systems such as the LPS. The count rate capability may be increased, with some corresponding reduction in the power duration, by modifying the electronics and on-board firmware. The addition of a small Geiger-Müller tube in the detector assembly would also allow accurate dose estimations over a large range, allowing users to carry a single instrument for detection, identification, and personnel protection. Larger CLYC crystals now available could be utilized to extend the useful gamma-ray efficiency range of a similar device. We will explore these concepts further in future efforts.

Acknowledgments

We thank Duane Balvage and Rick Lundy for their help in creating the circuit board designs for the LPS, and Daniel T. Keller for his help configuring and testing the Wi-Fi module. This work was supported by the Defense Threat Reduction Agency (DTRA), competitively awarded under HDTRA1-12-NTD-BAA. This support does not constitute an expressed or implied endorsement on the part of the U.S. Government. Pacific Northwest National Laboratory (PNNL) is operated for the US Department of Energy by Battelle under Contract DE-AC05-76RL01830. PNNL document number: PNNL-SA-113450.

Appendix A

Along with several other scintillators, CLYC can distinguish gamma-ray and neutron interactions via PSD. A standard figure of merit (FOM) has been defined to characterize the quality of the results [19]. Ideally, the PSD technique should produce a histogram with two distinct peaks, corresponding to gamma rays and neutrons. The distance between the peak centers, c_γ and c_n , should be large relative to FWHM values, w_γ and w_n . The FOM is defined accordingly:

Table 4: Typical specifications for the LPS.

Overall dimensions	$22 \times 19 \times 11.5 \text{ cm}^3$
Inner dimensions	$18 \times 13 \times 7.5 \text{ cm}^3$
Total weight	1.7 kg
Dynamic range	20-3500 keV
Combined energy resolution	6.5%
Gamma rejection ratio	10^{-7}
Maximum dose rate (662 keV)	24 $\mu\text{Gy/hr}$
Maximum count rate	$\sim 3800 \text{ cps}$
Warm-up time	2 min
Time to full calibration	11 min
Temperature range	-18 to 49°C
Temperature shock (inst.)	$\pm 21^\circ\text{C}$
WiFi power	21 dBm
DC power input	6.2-16 VDC
Batteries	Six AA alkaline
Battery lifetime (Wifi on/off)	29 hr / 41 hr
Data storage (full spectra)	18 hr
Internal calibration source	^{22}Na , $< 10 \text{ nCi}$

$$FOM = \frac{|c_n - c_\gamma|}{w_n + w_\gamma}$$

A related statistic is the gamma rejection ratio (GRR). This quantity represents the fraction of gamma rays that are misidentified as neutrons. Converting the FOM into the GRR is possible if the gamma and neutron peaks are Gaussian. Assume without loss of generality that $c_\gamma < c_n$. Now define a threshold t that separates the gamma-ray and neutron peaks. The optimal threshold, in terms of minimizing the number of misidentifications of either type, is located an equal number of standard deviations away from each center point:

$$\frac{c_n - t}{\sigma_n} = \frac{t - c_\gamma}{\sigma_\gamma}$$

It follows that

$$t = \frac{c_n \sigma_\gamma + c_\gamma \sigma_n}{\sigma_n + \sigma_\gamma} = c_\gamma + (c_n - c_\gamma) \frac{\sigma_\gamma}{\sigma_n + \sigma_\gamma}$$

Since $w = (2\sqrt{2\ln 2})\sigma$,

$$t = c_\gamma + (c_n - c_\gamma) \frac{w_\gamma}{w_n + w_\gamma} = c_\gamma + w_\gamma \cdot FOM$$

The number of standard deviations between c_γ and t is

$$\frac{(c_\gamma + w_\gamma FOM) - c_\gamma}{\sigma_\gamma} = 2\sqrt{2\ln 2} \cdot FOM$$

Table A1: PSD figure of merit and gamma rejection ratio.

FOM	GRR	GRR	FOM
0.500	1.195×10^{-1}	1.000×10^{-1}	0.544
1.000	9.266×10^{-3}	1.000×10^{-2}	0.988
1.500	2.060×10^{-4}	1.000×10^{-3}	1.312
2.000	1.241×10^{-6}	1.000×10^{-4}	1.579
2.500	1.966×10^{-9}	1.000×10^{-5}	1.811
3.000	8.062×10^{-13}	1.000×10^{-6}	2.019
		1.000×10^{-7}	2.208
		1.000×10^{-8}	2.383
		1.000×10^{-9}	2.547
		1.000×10^{-10}	2.701
		1.000×10^{-11}	2.848
		1.000×10^{-12}	2.987

The probability that a gamma event falls above t into the neutron region is

$$GRR = Q(2\sqrt{2\ln 2} \cdot FOM) = \frac{1}{2}\text{erfc}(2\sqrt{\ln 2} \cdot FOM)$$

Note that this result is equivalent to the probability that a neutron event falls below t into the gamma region.

Table A1 may be helpful for reference. For high values of the FOM, any non-Gaussian long tails or other artifacts in the peaks will affect the actual GRR.

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