Polaris-H Measurements and Performance

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***Abstract*–Polaris-H, a compact Compton camera designed by H3D, Inc. has been characterized and tested in field measurements at nuclear power plants. Polaris-H integrates a 3D-position-sensitive pixelated CZT detector (20 mm × 20 mm × 15 mm), associated readout electronics, an embedded computer, a 5-hour battery, and an optical camera all within a portable water-resistant case. The total mass is about 4 kg. Start-up time is 2 minutes. Additionally, there is a connection for a tablet, which displays a real-time gamma-ray spectrum (near 1% FWHM at 662 keV) and isotope-specific images of the radiation distribution in all 4π in real time. The newest design of Polaris-H features the capability to control data acquisition without using a tablet interface, a higher energy dynamic range, and a higher maximum count rate. Absolute efficiency, imaging efficiency, energy resolution, and detection and identification performance are presented. Measurements are shown for applications of decontamination and detection of previously unknown contamination regions.**

I. Introduction

THREE-dimensional-position-sensitive CdZnTe (CZT) detectors were first introduced over a decade years ago [1]. This technology is based on using small anode pixels and a large planar cathode on a thick CZT crystal. The resulting weighting potential for each pixel increases rapidly upon approaching the pixel, while the weighting potential for the cathode is linear with depth [2]. Therefore, the drift of an electron cloud formed from a gamma-ray interaction in the CZT will produce a signal on the cathode immediately but on the pixel only when it nears the pixel. The final signal amplitude on the cathode is proportional to depth and charge, but the signal on the anode is only proportional to charge. Using these signals, the energy deposited can be found from the charge deposited which is extracted from the anode signal amplitude, and the interaction depth is determined by the time between the cathode and anode signals or the ratio of cathode to anode signal. The pixel that is triggered tells the lateral position of the interaction. This allows the 3D location of each interaction in the crystal and the energy of each, even for multiple simultaneous interactions under different pixels. Energy calibration can therefore be performed on a voxel-by-voxel basis (producing energy resolution significantly below 1% FWHM at 662 keV using low-noise readout [3]) and multiple interactions from one gamma can be recorded (permitting Compton imaging over all directions simultaneously [4]).

After many years of research on materials, mounting, readout, event reconstruction, calibration, and imaging, this technology has matured into a commercial product – Polaris-H. This portable detector system, originally designed for the nuclear power market, enables a number of innovative applications. In this paper, we will describe the general hardware and software configuration of the fieldable system, then we report performance, and finally we will present several example measurements which demonstrate some of the capabilities of Polaris-H.

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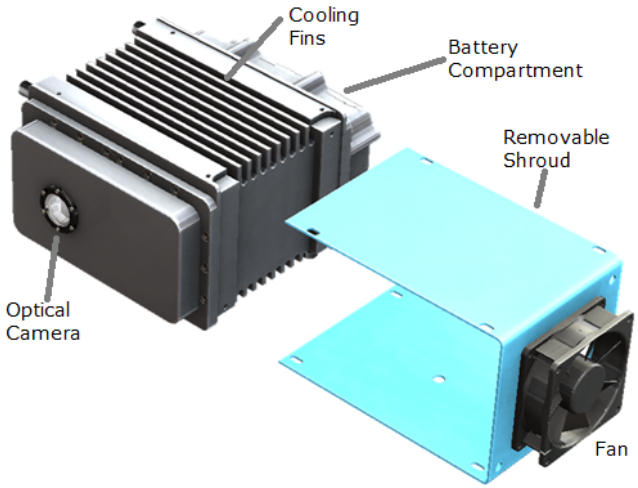

Fig. 1. Computer-aided drawing of the Polaris-H enclosure. The shroud and fan assembly slides over the main enclosure body to provide a pathway for air blown by the fan.

II. Hardware Design

Polaris-H has features to make it practical for use in contaminated areas of nuclear power plants. Fig. 1 shows a drawing of the unit, with major features labeled.

For the system to be used in the field, it must be self-contained and portable. The entire enclosure is 3.9 kg and can run on its battery for five hours. A carrying handle allows it to be carried with one hand. All data analysis and storage is done with an embedded computer, so it can take measurements for later analysis without any other supporting electronics. A button on one side of the unit can be pressed to mark new measurements or times of interest in the measurement. If one wishes to view the real-time results, a tablet computer can be connected wirelessly (through Wifi or Bluetooth), or via a USB cable to Polaris-H.

To be allowed in contaminated environments, it should repel dust and be easy to clean. Therefore, Polaris-H was designed to be water and dust resistant, with no air circulation to the inside volume. Rubber O-rings are used to seal all openings. Instead of air circulation, heat is dumped to a central aluminum wall, which is connected to heat fins on the

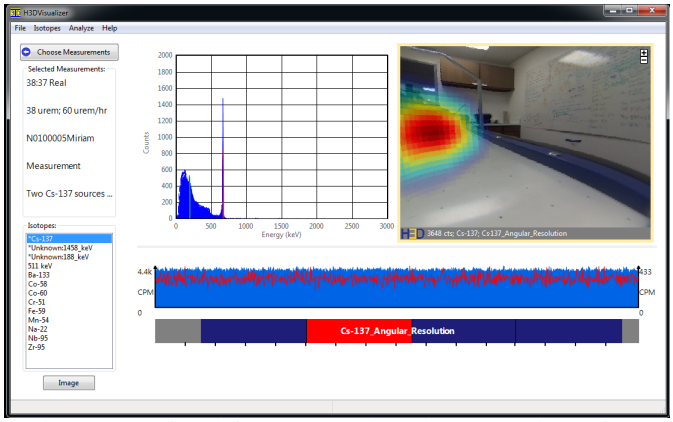

Fig. 2. Screenshot of the post-processing software. Starting in the upper left and moving clockwise, there are controls for viewing measurement meta-data, viewing the spectrum, viewing the image, viewing count rate vs. time and controlling time analysis of the data, and selecting isotope(s) to image.

outside of the enclosure. An aluminum shroud slides over the fins, allowing a fan to blow air efficiently over them. If contaminated, the shroud can be removed for cleaning.

An optical camera on the front of Polaris-H is used to overlay optical and radiation images in the front 2π of the field of view. A more complete description of the hardware design can be found in [5].

III. Software Design

An imaging spectrometer presents more information than a standard spectrometer, which can complicate the user interface. Beyond a spectrum, there is an image for every isotope. Potentially, these may also be viewed as a function of time. It is unrealistic to try to view all this output at once, so quick ways of switching between images for different isotopes and time bins need to be available.

In real-time, data is organized into "measurements" in which the detector should be kept stationary as it acquires images for each isotope. Notes can be saved for each measurement, and at any time during the measurement, the current state of the spectrum, optical, and radiation image can be saved along with notes about why this time point was of interest. At the beginning of each measurement, the spectrum and images are cleared and then build up in real time for each isotope in the library. If a new spectral line is detected that was not in the library, the image begins to be collected for that line as well. An "isotope" page allows quick switching between isotopes to view these images. Again, a more thorough overview of the real-time software can be found in [5].

Additionally, post-processing software allows review of the saved time points, combination of measurements, and time analysis of the measurements. A screenshot is shown in Fig. 2.

IV. Performance

Energy resolution of Polaris-H is reported in [5]. It is near 1% FWHM at 662 keV. Efficiency and imageable fraction are also reported in [5]. Photopeak efficiency is similar to that

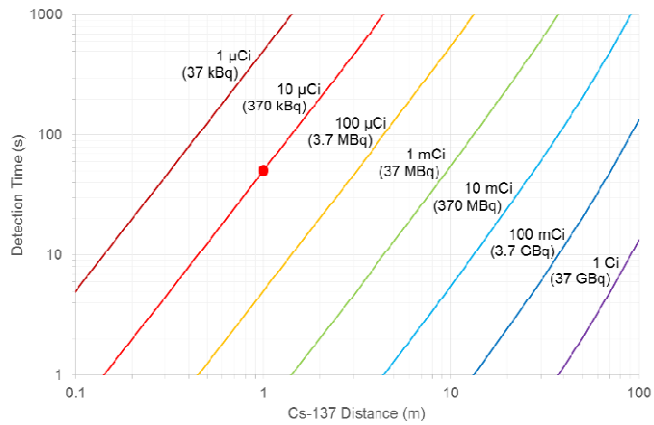

Fig. 3. Time to detect and identify a Cs-137 source as a function of source strength and distance, extrapolated from the marked point.

found in [6] for bare CZT crystals, but more attenuated at low energies due to the water-resistant aluminum box. The imageable fraction reaches 48% at 1333 keV.

Though the efficiency is lower than larger scintillator detectors, better energy resolution helps detection of weak photopeaks. With a false alarm rate of less than 1 per hour in a series of 1-minute measurements in laboratory background, a 10 µCi Cs-137 point source at 1 meter could be detected within a minute in 90% of trials. This detection performance is extrapolated to other source strengths and distances using geometry and air attenuation in Fig. 3.

Imaging angular resolution – the angle between two equally-intense point source of the same isotope that is needed to see two hot spots – is 30° in real-time imaging and 20° using post-processing algorithms. For finer discrimination of features, the detector must be moved closer to the source. Often, a parameter of more interest in the field is angular precision. Polaris-H can locate the center of a point source and match it to the optical image to within ±1° in any direction around the detector.

V. Example Measurements

In this section, example measurements collected from users in North America and Europe are presented to show various modes of operation.

A. *Residual-Heat-Removal Pump Room*

In this measurement, Polaris-H was placed on the floor of a room facing the pump. Data were recorded for 10.2 minutes, in which time 2.3 x 10^6 counts were collected. The dose rate here was about 0.4 mrem/hr. Fig. 4 shows the results.

The spectrum in Fig. 4a shows the presence of Co-58, Co-60, and Cs-137. Taking a narrow energy window around the Co-58 photopeaks and imaging all multiple-interaction events in this window produces the image in Fig. 4b. It is clear that the bottom part of the pump is the primary direction from which Co-58 gamma rays come from. Doing the same for the Co-60 photopeaks in Fig. 4c, a different region of the bottom of the pump appears hot. From these distributions, one can infer something about the contamination events. Because both cobalt isotopes transport chemically the same, but their decay

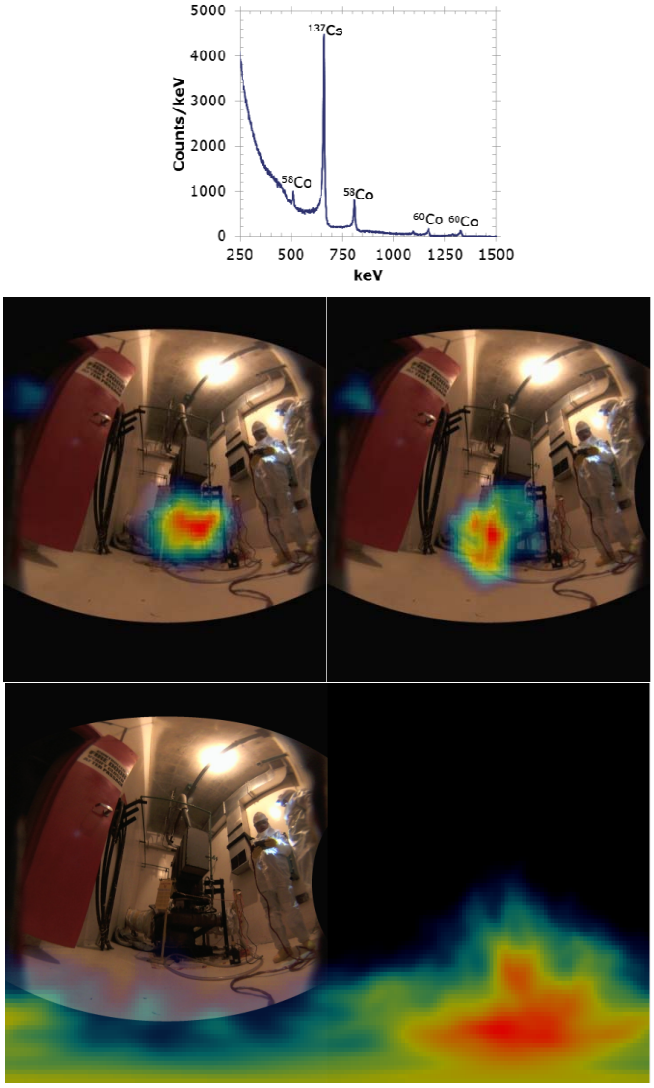

Fig. 4. Measurement of the Residual Heat Removal Pump Room. From top to bottom and left to right: (a) The spectrum of all events; (b) The image of Co-58; (c) The image of Co-60; (d) The image of Cs-137. (b) and (c) are images showing the front 2π of directions. There is no significant image in the backward direction. Image (d) shows all 4π directions in an equirectangular projection.

half-lives differ, we know that at least two separate events caused this contamination, otherwise the spatial distribution of the two would be the same. Because it has the shorter half-life, the Co-58 distribution may be from the more recent contamination event.

Finally, the Cs-137 distribution in Fig. 4d shows Cs-137 contamination on the floor. This is from a known flood in the room which deposited this isotope on the floor and lower wall. Hot regions only appear on the floor closest to the detector because of geometric attenuation.

This measurement shows the ability of the system to perform isotope-specific imaging. This allows "radiation forensics" where the history of the contamination events can be ascertained.

B. Shield Verification

Another application of Polaris-H is to determine whether shielding is working as designed. In this example

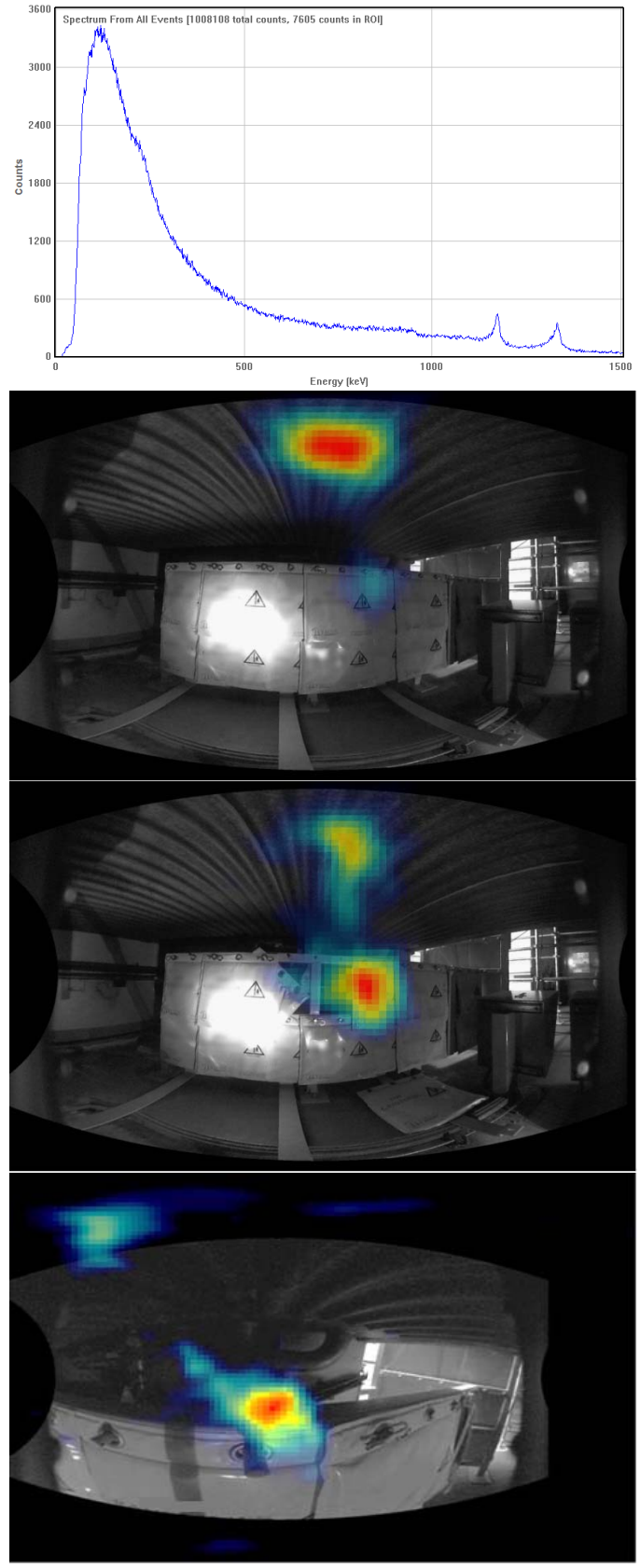

Fig. 5. Measurements around shielding of a pipe. From top to bottom: (a) The spectrum of all events for the case with shielding in place; (b) The Co-60 image after 30 s with a piece of the shield removed; (c) The image of Co-60 after 1 minute with the shield fully in place; (d) The image of Co-60 after 30 s looking over the shield at the pipe. All are images showing the front 2π of directions. There is no significant image in the backward direction.

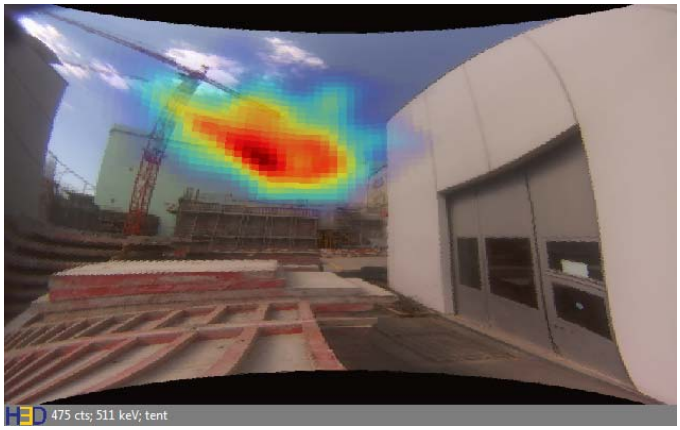

Fig. 6. The image of 511-keV photons outside a reactor building, in a 51-minute measurement.

measurement, a wall of shielding material was constructed in front of a hot piping unit. The user wanted to know whether the shielding was performing well.

Three measurements were taken. In the first, the shield was present, and the measurement lasted one minute. The spectrum in Fig. 5a shows that the only significant isotope is Co-60, but there is also significant scattered continuum, presumably from scatter in the shield and other materials. If we image events in the photopeak regions of Co-60, we see the image in Fig. 5b, which shows a strong hot spot coming from above (from a known source in the room above) and a much weaker hot spot from the direction of the shield. This tells us that, at least in terms of direct emissions, there is little advantage of adding more shielding to the source in this room, as the source in the room above contributes much more to the direct gamma ray field at the sensor.

Of course, scattered gamma rays also contribute to the dose, but the quantity of un-scattered flux tells the most about the dose because both scale with shield thickness. Furthermore, the high energy gamma rays contribute more to the dose and because this is a high-Z shield, there is a relatively low amount of scatter.

In a 30-s measurement, a portion of the shield was removed to verify that the shield was having an effect. Now, in Fig. 5c, the hottest direction of Co-60 is from the object that was previously shielded and a relatively weak source is in the room above. In this case, since the source in this room is the strongest, adding shielding would help to decrease dose. The shield that was constructed is effective.

Finally, Fig. 5d shows the view when looking over the shield with Polaris-H for 30 s. Again, the only isotope present is Co-60. This view shows that it is possible to localize the hottest segment of pipe. It might be possible to use less shield material and only shield this one segment.

C. *Sky-Shine*

An interesting measurement to show the sensitivity of Polaris-H is to image sky-shine outside the plant. Fig. 6 shows the image of 511-keV photons recorded in a 51-minute measurement outside a reactor building. High-energy gamma rays, such as those from N-16 decay, interact in the air above the reactor building by pair production, eventually producing the imaged 511-keV photons, which are then imaged.

VI. Conclusions

A new commercial detector, Polaris-H has been designed and tested for use in nuclear power plants. Its hardware features makes it useful for work in contaminated and confined environments. Performance was presented, which has near 1% FWHM energy resolution at 662 keV and the ability to localize point sources to with ±1° in any direction. Though less efficient than larger detectors, it has the ability to detect a 10 μCi Cs-137 source at 1 m in less than 1 minute because of its good energy resolution. Examples were presented to show its capabilities to produce isotope-specific images in real nuclear power plant environments and in seeing weak sources such as sky-shine. These are useful for a number of applications, including determining regions of contamination and trying to understand the history of contamination events and verifying shielding. Other applications of finding unknown sources and monitoring shipping containers holding sources have also been successfully attempted. Future work will continue to apply this technology to nuclear-power measurements by improving software and hardware and learning about how to best apply this technology to the needs of nuclear power.

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