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AN IMAGING NUCLEAR SURVEY SYSTEM

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Abstract

A combined video and gamma ray imaging system has been developed to rapidly determine the location, distribution, and intensity of gamma ray sources. This instrument includes both a conventional video camera and a gamma ray imaging system, which is based upon a position sensitive photomultiplier tube, a scintillator, and a pinhole collimator. The gamma camera records the position and energy of each interaction, determining the energy spectrum and count rate from each direction. The design of the instrument and results of preliminary field tests will be presented.

We have used a prototype of such an instrument in preliminary field tests to image radioactive sources with gamma ray energies between 120 keV and 2.4 MeV. This new system achieves an angular resolution for the nuclear image of 6° with an efficiency of $3x10^{-6}$ at 1 meter, a performance suitable for many nuclear applications. The sensitivity of the system is sufficiently high that, in a low background environment, a 1 mCi ^{137}Cs source at 5 meters can be located in <30 seconds. Alternatively, higher spatial resolution can be attained at lower efficiency and longer imaging times.

I. Introduction

Modern nuclear survey instruments are useful for making rapid, discrete point measurements of radiation intensity, but do not give directional information regarding the radiation. This frequently makes locating a source cumbersome and time-consuming and does not allow the operator to easily visualize the distribution of radioactivity in the local environment. We have developed an instrument which overcomes these difficulties. This device combines a video camera with a portable gamma ray imaging system to produce an image of the radioactivity, superimposed on a video image of the same field of view, thereby allowing an operator to rapidly and remotely locate radioactive sources. The instrument also determines the energy of the gamma rays, allowing an operator to distinguish the locations of different isotopes, to identify isotopes in the field of view, and to determine dose rate and source activity.

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II. Instrument Design

This portable imaging survey system combines a gamma ray imaging system with a conventional video camera and personal computer-based data acquisition and display unit. A block diagram and a photograph of the instrument are shown in figures 1 and 2. The gamma ray imager is based upon a position sensitive photomultiplier tube (PSPMT) coupled to a scintillator and collimator, with radiation shielding to minimize the contribution of background and scattered radiation. Because the PSPMT is only 3" in diameter, the gamma ray imager is sufficiently small and light to be transportable [1]. The PSPMT is a single photon imaging device, with each incident light pulse producing analog output pulses from which the position and energy of the incident gamma ray can be computed. Because the PSPMT outputs also contain energy information, one can find the energy spectrum as a function of position, or can separately image isotopes which emit at different energies.

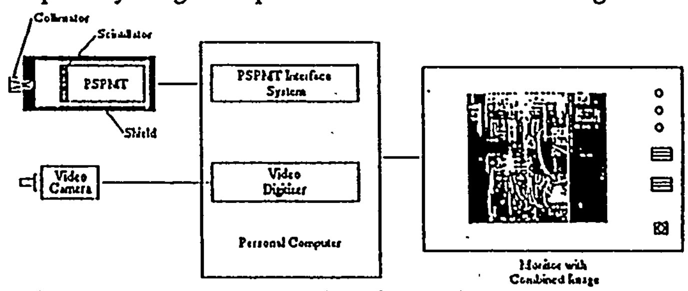

Figure 1. Block diagram of imaging nuclear survey system.

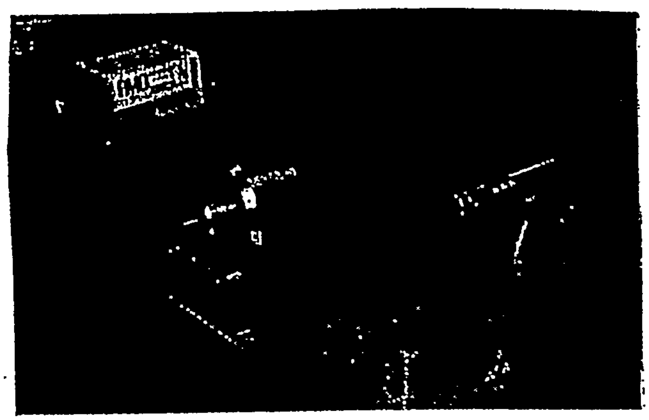

Figure 2. Photograph of the field prototype of the imaging nuclear survey system. A conventional survey meter is shown for a size comparison.

In order to obtain positional information, a collimator and shield are used to restrict the solid angle which may illuminate an image pixel. The present field prototype uses a pinhole collimator with a double conical hole machined in tungsten (see figure 1). The cone allows imaging throughout the field of view with no attenuation. A pinhole collimator has several advantages over other types, including ease of fabrication, ease of operation, and angular resolution independent of distance (which allows straightforward comparison of the nuclear and video images). The primary factor which determines the efficiency and spatial resolution of the system is the angle subtended by the collimator pinhole, with smaller pinholes having higher resolution and lower efficiency. Because some applications stress high spatial resolution while others stress high efficiency, the collimator is threaded into the shielding, allowing the operator to rapidly exchange collimators in the field to optimize the instrument for specific applications. The instrument can be readily adapted to handle other collimator designs, such as diverging multiple hole collimators [2, 3].

At high energies, penumbral penetration through the edges of the pinhole is a limiting factor for image quality. We have modeled the response of the collimator using the EGS4 Monte Carlo simulation code [4]. For example, we have analyzed a collimator made from 4 cm of tungsten with a 7 mm pinhole, adjusted to provide a 7 meter diameter field of view at a 10 meter distance. At 100 keV the angular resolution can be shown to be 5.2°, while at 1 MeV the angular resolution is 6.5° due to penumbral penetration. The geometric efficiency is determined by the solid angle subtended by the pinhole, as seen from the source. For a 7 mm pinhole, the extrinsic efficiency at 1 meter is $3x10^{-6}$. The distance from the front of the collimator to the PSPMT determines the angular field of view. We have designed the housing of the field prototype so that this distance can be adjusted between 3 cm and 12 cm, allowing a conical field of view ranging from 24° to 90°.

The use of the collimator leads to a requirement for good shielding to protect the rear of the scintillation crystal from incident radiation. This need arises because the pinhole in the collimator greatly reduces the count rate due to the source, while in the absence of shielding, the scintillator is sensitive to background counts incident from the $>2\pi$ solid angle behind the detector. The effectiveness of this shielding has a strong bearing on the time needed to acquire a useful image, since the pixels representing the source must have a signal to total noise ratio which exceeds a threshold of three. The signal is the number of counts due to the source minus the background, while the total noise is the uncertainty due to source plus background. The presence of background radiation thus has a significant impact on imaging time. When imaging most sources in high background environments, or when imaging very weak sources in normal backgrounds, shielding must be placed around the scintillator and PSPMT in order to minimize the count rate due to background radiation. In the instrument shown in figure 2, a lead shield encloses the PSPMT and scintillator, except for the pinhole and an indirect hole where the power and signal wires pass. The shielding provides two attenuation lengths at 662 keV, while keeping the total instrument weight below 30 kg. This shield is suitable for many applications, but additional shielding can be added if desired. Various shielding options have been considered, including a cylindrical shield of depleted uranium which would allow operation at background dose rates of several R/hr. We have found that the performance of the system can be significantly improved by the addition of a ring of shielding around the scintillator. Simulations show that the ring reduces the flux by a factor of approximately two, for ^{137}Cs and ^{60}Co, with little increase in weight.

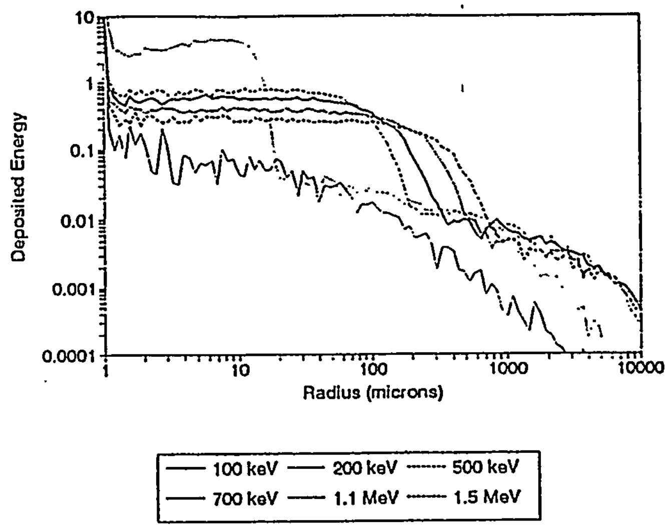

Figure 3. Plot showing the simulated radial distribution of deposited energy in the BGO scintillator.

In order to provide good stopping power for gamma rays with energy above 1 MeV, it is necessary to use a thick scintillator. However, the use of a thick crystal would ordinarily significantly degrade the resolution of the nuclear image. This is due to light spreading in the scintillator, combined with the fact that the uncertainty in the event location is inversely proportional to the area over which the light is spread [1,5,6]. For this reason, we have used a segmented scintillator. The scintillator is made of 1 cm thick BGO to yield 50% stopping at 1 MeV. The segments are 2.5 mm on center, separated by (MgO) optical reflector material. Photons generated within a given segment are always distributed uniformly over a 6.25 mm^2 area of the photocathode. For gamma ray energies between 0.1 and 1 MeV the measured PSPMT spatial resolution varies between 1 and 2.5 mm. To obtain good statistics and good resolution for photon energies >0.1 MeV, the segment size, which determines the maximum pixel size, is half the dimension of the pinhole. It is also important that the segment size be larger than the range of the secondary particles, otherwise the segmentation is not useful. To design the segmented scintillator we used the EGS4 model to compute the radial distribution of energy, assuming a beam of particles perpendicularly incident at a point on the face of the crystal. The results of this analysis, shown in figure 3, indicate that even at 1.5 MeV virtually all of the energy is deposited within 250 μm of the point of incidence.

Due to the low light output of BGO and to the low optical efficiency of the segmented scintillator, the energy resolution of the present system is limited to approximately 25%. Figure 4 presents two energy spectra obtained with the segmented BGO crystal, showing a 662 keV peak for ^{137}Cs and the 511 and 810 keV peaks of ^{58}Ni. In applications demanding higher energy resolution, other scintillator materials may be used, including NaI(Tl) and CsI(Na). An unsegmented NaI(Tl) scintillator has been measured to yield 12% energy resolution, using a position dependent gain correction [2,6]. However, an unsegmented scintillator must be made thin to avoid light spreading, and so has lower efficiency. There is thus a trade-off between energy resolution, spatial resolution, and detection efficiency, depending on the application. The instrument can be used with any of these scintillator materials and geometries.

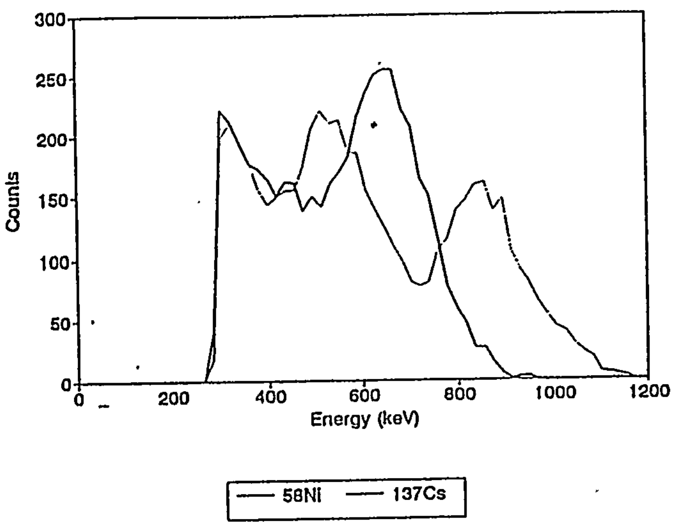

Figure 4. Energy spectra obtained using the PSPMT with segmented BGO scintillator, demonstrating the ability to separate distinct gamma ray peaks.

In this instrument the PSPMT is interfaced to the personal computer using an improved version of a commercially available PSPMT interface system [7]. Using the previously available interface, significant image distortion due to baseline shift was observed at high count rates. The improved interface includes bipolar shaping amplifiers for each output from the preamplifier, allowing high quality images to be obtained at high count rates. In operation, the Interface System acquires digitized coordinate and energy values, implements a position dependent energy discrimination and a uniformity correction to compensate for the non-uniformity of the PSPMT, and places the nuclear image into a buffer in the computer. The video image is displayed in gray scale on the monitor, while the nuclear image is displayed in color, superimposed on the video image in real-time. The colors of the nuclear image make it easier for the user to rapidly locate the source.

Energy discrimination is quite important in rejecting scattered radiation to obtain high quality images. However, because the gain of the PSPMT varies with position, software correction is used to carry out a separate pulse-height discrimination for each spatial pixel [2,8]. In this way only events within a ±15% energy window around the photopeak are accepted in each pixel. This greatly reduces the radiation which scatters off surrounding objects or the collimator. In addition it allows one to image a high energy source in the presence of a low energy source. The energy window can be modified in the field, allowing acquisition and display of separate nuclear images for each isotopic energy. In applications where the energy of the source is not known, it is possible to first scan the area without energy discrimination to obtain a preliminary image with somewhat degraded image quality. The software also allows the operator to obtain an energy spectrum from each spatial pixel. This can be used to compute the dose rate incident from each direction, by applying standard conversion factor [9]. If the distance can be judged, then the source activity can be estimated. The energy spectra can also be used to determine the identity of each source, using a spectrum fitting algorithm [10].

Figure 5. Combined video and gamma ray image of deionizing tank in the Ford Research Reactor, showing the distribution of ^{24}Na. Image was obtained from 5 meters distance in two minutes.

III. FIELD RESULTS

In preliminary laboratory tests, we obtained images of several weak isotopic sources located one meter from the camera. During these tests the same collimator and scintillator were used, with only the energy discrimination changed between images. In these tests the system imaged 80 μCi of ^{60}Co (1.17 and 1.32 MeV) in 20 minutes, 1 mCi of ^{137}Cs (662 keV) in 30 seconds, and 8.5 mCi of ^{57}Co (122 keV) in 5 sec [2]. This clearly demonstrated the ability of the system to image a wide range of gamma ray energies, from 122 keV to 1.3 MeV. At higher energies reduced spatial resolution was observed, due to additional penetration through the conical aperture in the collimator. The measured angular resolution was 6°, implying a spatial resolution of 10 cm at 5 m distance.

More recently the instrument was used in preliminary field tests to image radioactive sources in realistic environments. Figure 5 shows the distribution of ^{24}Na in a reactor deionizing tank. The image was obtained at a distance of 5 meters in a 10 mR/hr background in the equipment room of the Ford Nuclear Reactor, at the University of Michigan, Ann Arbor. Untrained individuals could locate the source in less than 10 seconds. Figure 6 shows a similar image of activated steel obtained in a hot cave at the Phoenix Memorial Laboratory. In many applications it is desirable to image distributed sources, rather than point sources. Figure 7 presents an image of a distributed source, a ^{198}Au wire bent into the shape of an M. The asymmetric shape is due to the asymmetry in the wire.

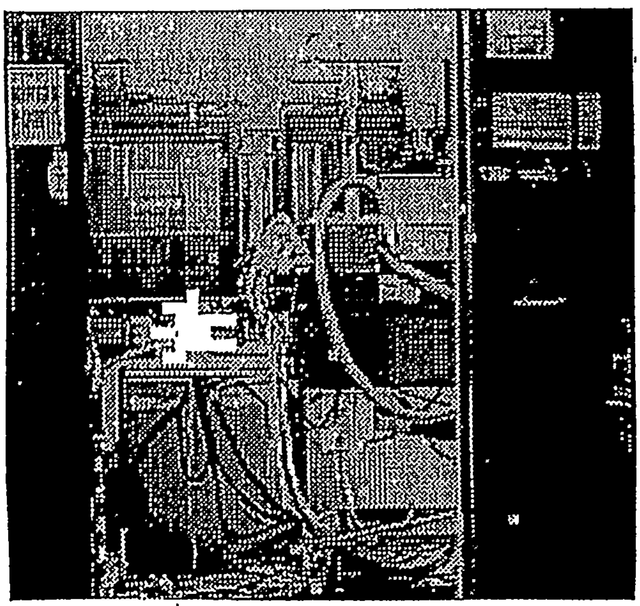

Figure 6. Combined video and nuclear image of activated steel in a hot cave at the Phoenix Memorial Laboratory.

IV. Conclusions

A portable imaging nuclear survey system is being developed, which combines a gamma ray image of the distribution of radioactivity with a video image of the area. The gamma ray imaging system is based upon a position sensitive photomultiplier tube, a segmented BGO scintillator, a pinhole collimator, and radiation shielding. This system which provides high quality images, with spectroscopic information, from 0.1 to 1.5 MeV. A prototype of the system was fabricated and tested and a Monte Carlo model developed to optimize its performance. We have acquired good quality images with gamma ray energies from 0.1 to 1.3 MeV and have measured the performance of the system in preliminary field tests. This system has demonstrated the spatial resolution and efficiency required for many applications in nuclear industry.

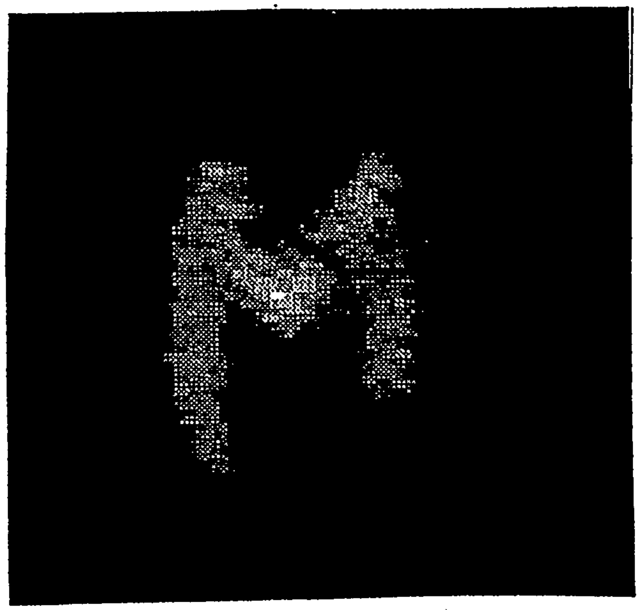

Figure 7. Nuclear image of a ^{198}Au wire, showing the capability to image distributed sources.

V. References

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