APPLICABILITY OF COMPTON IMAGING IN NUCLEAR DECOMMISSIONING ACTIVITIES

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ABSTRACT

During the decommissioning of nuclear facilities significant part of the activities is related to the radiological characterization, waste classification and management. For these purposes a relatively new imaging technique, based on informations from the gamma radiation that undergoes Compton scattering, is applicable. Compton imaging systems have a number of advantages for nuclear waste characterization, such as identifying hot spots in mixed waste in order to reduce the volume of high-level waste requiring extensive treatment or long-term storage, imaging large contaminated areas and objects etc.

Compton imaging also has potential applications for monitoring of production, transport and storage of nuclear materials and components.

This paper discusses some system design requirements and performance specifications for these applications. The advantages of Compton imaging are compared to competing imaging techniques.

Key words: decommissioning, waste characterization, Compton imaging, gamma detector, Compton camera

1. Introduction

Compton imaging is a visualization technique that uses the kinematics of Compton scattering for the reconstruction of a gamma radiation source image [1]. Compton imaging systems, also known as Compton cameras, are used in the nuclear power industry for site and environmental surveys, in gamma-ray astronomy [2] and in several prototypes of nuclear medical imaging systems [3,4].

Basic design of Compton imaging systems consists of two planes of position sensitive and energy dispersive gamma-ray detectors. Electronic collimation gives the possibility to perform gamma-ray imaging without use of mechanical collimators. Usefull informations for the reconstruction of gamma source distribution are brought by the gamma photons that undergo Compton scattering in a first detector and then absorption in a second detector.

The potential advantages of the Compton cameras over conventional imaging techniques include a large field of view, increased efficiency, good background suppression and a more compact and lightweight imaging system. Compton cameras are effective over a large energy range (140 keV to 10 MeV) and can be used in an energy selective mode for the separate imaging of the mixed gamma-ray sources. At close ranges (less than few meters) they give possibility for three-dimensional (3D) imaging of objects from a fixed position without detector motion.

The concept of an electronically collimated gamma camera was introduced in nuclear medicine during the seventies and was investigated experimentally [5,6] and theoretically [7-9] during the eighties. The first Compton camera was designed for medical imaging as a replacement for heavy lead collimators in SPECT (Single Photon Emission Computing Tomography) using 140 keV gamma rays [3,4]. It was shown that the replacement of the passive parallel hole collimator by an active detector leads to an increased sensitivity. The use of a germanium detector for the front plane and a large position sensitive NaI detector for the back plane provided an improvement in sensitivity by a factor of 25 over conventional SPECT [5]. A systems were investigated in which the back detector was replaced by an array of NaI detectors and resolution of 1.5 cm for ^{137}Cs gamma-rays was achieved [10]. If germanium detector arrays are used for both the front and back planes of the Compton camera, possibility for three-dimensional imaging of several sources with different energies and intensities can be demonstrated.

2. Principle of Operation

In general Compton imaging systems consist of two or more detectors separated by the order of 10 cm to 1 m. Kinematics of Compton scattering of gamma photons is used for the reconstruction of a gamma-ray source image without the use of collimators or masks. An useful event for the obtaining of an image consists of detection of the energy and position of a Compton scattering in the front plane (scattering detector), followed by detection of the residual energy and position of the scattered gamma ray in the back plane (absorption detector). These two detection have to satisfy coincidence requirements. Sum of the energy release in both detectors defines the initial gamma-ray energy and can be used for the discrimination of parasite gamma photon contribution.

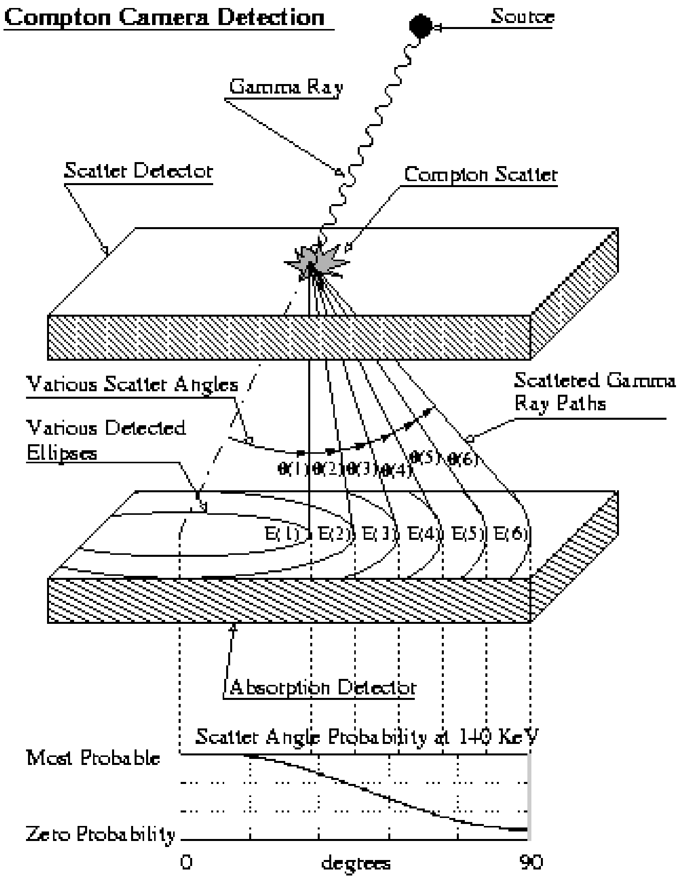
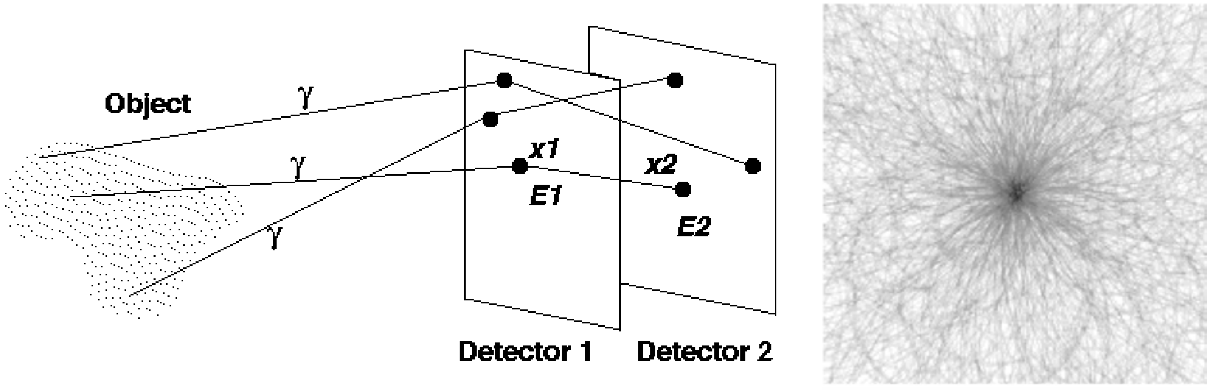


Figure 1. *Principle Setup of a Compton Camera*



(a) (b)

Figure 2.*(a) Principle of Compton Camera Image Reconstruction;*
(b) Image of Point Gamma-Ray Source Reconstructed by Backprojection of Cones

The positions of the interactions, coupled with the scatter angle, limits the possible locations of gamma photon emission point to a cone whose axis is in line with the positions of the two interactions, and whose opening angle is equal to the scatter angle θ:

$$cos(\theta) = 1 - \frac{m_e c^2 \Delta E}{(E - \Delta E)E}, \tag{1}$$

where m_e is mass of electron, c is velocity of light, E is initial gamma photon energy and ΔE is energy loss in Compton scatter event in first detector. Uncertainties of the determination of positions and energies lead to a non-zero thickness of this cone of possible source locations.

The source image is then reconstructed by the backprojection and intersection of number of conic surfaces in the image space. This type of information about the possible source distribution requires specialized reconstructions techniques. These techniques are under investigation by a number of research groups [11,12].

3. Gamma Sources of Interest and Applications

Gamma sources which distribution can be obtained by the Compton imaging systems during the radiological characterization of nuclear materials are listed in Table 1.

Table 1. *Gamma Rays of Interest for Compton Imaging of Nuclear Materials*

Nuclide	Half-life [year]	Gamma Energy [keV]
^{232}U	68.9	538, 2615
^{235}U	7.038 10^8	186
^{238}U	4.468 10^9	766, 1001
^{239}Pu	2.411 10^4	375, 414
^{241}Pu	14.29	208, 662, 723
^{137}Cs	30.07	662
^{152}Eu	13.516	344, 779, 964, 1112, 1408
^{154}Eu	8.592	723, 873, 996, 1005, 1274
^{60}Co	5.27	1173, 1332

Compton imaging has been demonstrated at energies of 140 keV for nuclear medical applications, but this technique is more practical for energies above 300 keV up to several MeV. At low energies collimators or masks are effective, but they become impractical above a few hundred keV due to significant penetrating of collimator septa. For the decommissioning applications this region of higher energies is interesting, where the imaging techniques based on mechanical collimation are not applicable.

First five nuclides given in Table 1 are present in the nuclear reactors as fuel materials. Uranium with the high enrichment in nuclide ^{235}U is hard to detect because of its low-energy gamma rays, which are easily shielded. Gamma ray energies of other nuclear fuel nuclides are in the effective range for Compton imaging. The most representative nuclides for the nuclear wastes generated during the reactor operation are listed in the rest of the Table 1. If the waste has been stored long enough for the decay of short half-life fission products, the main gamma activity contribution will originate from ^{137}Cs, ^{152}Eu and ^{154}Eu. Activation of stainless steel reactor components will produce ^{60}Co as the most important gamma activity source.

The large volumes of nuclear wastes have to be characterized as low, medium or high level radioactive before the disposal in final storage. Compton imaging can be used to identify hot spots in barrels of waste which can then be removed, allowing the remaining material to be disposed as low level waste. In that way cost of the waste disposal and also volume of high radioactive wastes can be significantly reduced. Compton imaging can also be used for the imaging of large contaminated objects, structures or sites. Hot spots can be identified on a contaminated walls or floors and then removed for separate disposal before the renovation or demolition of the building. It can also be used for overhead identifying and characterization of contaminated sites from cranes or helicopters.

Compton imaging could be used for inspection of containers or transport caskc in order to determine materials that can be used for nuclear weapons production. The ability to obtain an image of a large object from a fixed viewpoint is a significant advantage over other imaging techniques that require scanning of the containers.

4. Compton Camera Design Considerations

Compton imaging system uses fraction of the gamma photons emitted from the source object that undergoes Compton scattering in the scatter detector. Design request for the scatter detector material is therefore high Compton scattering cross section in the 100-600 KeV range. Adequate materials that have been proposed and investigated are Si, Ge and Ar. Other characteristics that have to be justified are material efficiency for single Compton events in relation to other interactions, detector energy resolution and detector position resolution.The choice of material and geometry of the scatter detector strongly affects system imaging capability.

After the interaction in front detector, the Compton scattered photon has to be registered in the back absorption detector, measuring both position and energy. Typical material choices for this detector are CdZnTe, NaI, BGO or Xe detectors because of their high cross sections for the photo-absorption in the energy range of few hundred keV's up to a few MeV.

Compton imaging uses time coincident signals from both scatter and absorption detector. Since exact energy of photon emitted from the source is known and the energies deposited at both detectors are measurable, the events of interest can be discriminated from the unwanted events, such as scattered photons within the source object or multiple scatters in front detector. Minimal set of information needed for image reconstruction consist of:

- energy deposed in the scatter detector (kinetic energy of Compton scattered electron);
- positions of scatter and absorption interactions.

The first absorbtion detector materials investigated were NaI and BGO. They have lower energy and position resolutions comparing to solid state and gas couterparts, but the good efficiency is reason for continuing of their consideration. Solid state detectors are being investigated for use in Compton cameras because of their high energy and spatial resolution compared to scintillation crystals. They usually have a smaller field of view (approx. 10 cm) than existing Anger cameras (50 cm). Considering all important characteristics, it seems that Si is the best solid-state choice for the scatter detector. Some of Si disadvantages are its sensitivity to the thermal noise and need of cooling in order to operate at acceptable levels of energy resolution. Thickness of Si detectors is limited to approximately 5 mm by the cost of production. Thick Ge detectors can be easily produced, but they are not optimal choice because of its high photoelectric cross-section.

Image resolution of Compton imaging system depends both on the energy resolution of the detectors and on the position resolution. Good resolution requires large detector arrays with both good energy resolution (1% or less) and good detection efficiency. These requirements are easily achieved by Ge detector arrays, but this solution require liquid nitrogen cooling, which is not always convenient for nuclear waste applications and may not be available at application sites. The alternative of mechanical cooling adds power requirements and weight to the system. Room temperature semiconductor detectors such as CdZnTe are approaching to energy resolution of 1%. At the moment it is still technical problem to produce high-resolution detectors in sizes large enough to stop the high-energy gamma rays necessary for nuclear materials imaging and further development is needed.

Position resolution of Compton cameras depends both on the size of the individual detector elements (pixels) and the separation of two detector planes. At one meter distance, a pixel size of 1 cm for the individual detector elements in the array gives position resolution of about 1%. For a more compact systems, smaller pixel size is needed. For a given pixel size, a larger number of pixels increases the efficiency and reduces the problem of image artifacts but adds to the complexity and cost.

The angular uncertainty for a gamma ray scattered at an angle θ, is inversely proportional to $\sin(\theta)$. Scatterings at small angles thus degrade image resolution and should be rejected. This suggests a sparse detector array with widely separated pixels. Large number of detector array elements significantly increases the requirements for electronic components and support. A number of application specific integrated circuits has been developed for space and industrial applications in order to reduce both power and weight requirements. Real-time Compton imaging also requires fast and efficient computer algorithms. The rapid advance in computer processing power along with the application of efficient parallel algorithms developed for medical imaging should satisfy this requirement.

The design of a Compton imaging system can be adjusted to the application. For characterization of nuclear waste barrels a resolution of a cubic centimeter is required. For wall scanning or site mapping, a much larger resolution may be sufficient. Producing a practical compact Compton camera with real time imaging capabilities for applications in nuclear waste management and nuclear material transfer control still requires a number of technical challenges and usage of some technical improvements being developed for medical, industrial and space applications.

There are several other imaging techniques that can be competitive with Compton imaging depending on the application. One of the widely used technologies with good image resolution is application of multiple pinhole camera with position sensitive NaI detectors. That system is dominantly used in SPECT where a single low-energy gamma rays of known energy are treated. This technique is limited to energies of few hundred keV and requires heavy collimation with small aperture size for the determination of the source position. Three dimensional image can be obtained only from the set of images for different angular positions. Relatively long counting times are required for low active sources. Energy resolution of the imaging system can be improved by collimated germanium detectors. An increased efficiency and field of view over a pinhole collimator can be obtained by a coded aperture mask that gives a possibility for simultaneous imaging of two gamma sources with different energies.

Detailed image of the distribution of the material densities in the nuclear waste barrels can be determined by active computed tomography (CT). This technique requires scanning of the object and access from the different angular positions. The main limitation for the application of active (transmission) CT for the imaging of nuclear materials is always present superposition of transmited and and emited gamma rays. Passive CT obtains the source distribution image from the gamma-rays emitted by the nuclear materials, without use of outer independent gamma ray source. If material within the investigated object is low-level waste, good quality image usualy requires very long counting time.

5. Conclusion

Compton imaging as visualization technique poses significant advantages for applications in nuclear waste characterization. It is completely passive and gives a 3D image of an object from a single viewpoint without needs for scanning or access to both sides of the object. It covers a large energy range, has a wide field of view and does not require mechanical collimation. Mixed radionuclide sources can be successfully separated by selectively imaging of gamma rays of interest. Compton imaging also provides good background suppression through the kinematics of the scattering process and through energy filtering. Decommissioning of a nuclear facilities includes wide range of activities where Compton imaging could be successfully applied.

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