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A Gamma-Ray Camera for Arms Control Applications

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A gamma-ray camera for arms control applications

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ABSTRACT

The Research Institute of Pulse Techniques, in collaboration with the Proliferation Prevention and Arms Control Program at Lawrence Livermore National Laboratory, has constructed a gamma-ray camera for use in arms control agreements such as Mutual Reciprocal Inspections and Warhead Dismantlement Transparency. The camera is designed to have high efficiency (in order to reduce inspection times), moderate resolution (to decrease the intrusiveness of the measurements), and sturdy construction (to allow operation in the types of conditions that might be met during shipment and use at various forward weapons sites). The imaging element consists of a honeycomb or soda-straw lead collimator and a 312-mm-diameter NaI(Tl) scintillator viewed by an array of phototubes. Software was developed to display two- and three-dimensional views of the data and to analyze shape and peak areas. The first model was tuned for plutonium radiation in the 375- to 415-keV energy range. Images from various arrays of point sources were obtained and will be presented.

Keywords: Gamma ray, Compton scattering, transparency, fissile material

1. INTRODUCTION

In March of 1994, Secretary of Energy O'Leary and Minister of Atomic Energy Mikhailov signed the Agreement on Mutual Reciprocal Inspections (MRI). This agreement called on both countries to host inspections at facilities storing fissile material from dismantled nuclear weapons. Its unexpected signing set off a two-pronged scramble, in both the policy and technical areas, to determine how to carry out this mandate. During the summer and fall of that year, representatives from U.S. and Russian Federation weapons laboratories met to determine those characteristics of fissile material that could be examined without opening closed containers, to lend confidence (transparency) to the fact that the material had been removed from a dismantled weapon. The experts began by considering only plutonium components, because they are more tractable than highly enriched uranium. Eventually, they decided on the characteristics of isotopic content, mass, and shape as providing the most confidence in the origin of the fissile material. Although the MRI agreement itself eventually foundered on the shoals of classification and other political issues, these characteristics have become canonized in the arms control arena as being indicative of weapons components.

In support of the MRI technical experts' meetings, two technical exchanges were held in the Plutonium Facility at Lawrence Livermore National Laboratory (LLNL). Each side brought candidate technologies for measuring the determined characteristics with minimal intrusiveness, and measurements were carried out on a large number of unclassified plutonium objects of varying shapes. While the two sides rapidly agreed on technologies for measuring mass and isotopics, there was never the same agreement on shape measurements. It became clear during later discussions that it would make the Russian Federation more comfortable to use imaging apparatus that had been designed and manufactured in Russia, presumably to allow the Russians control over the possible inclusion of clandestine elements within the system. In 1995, under the aegis of the U.S. Department of Energy (DOE) Lab-to-Lab Dismantlement Transparency Program, it became possible for LLNL and the Research Institute of Pulse Techniques (RIPT) to collaborate on the design and construction of a camera to be used exclusively for arms control inspections of fissile material, both within and outside of containers. This camera was meant to fulfill most of the conditions described above. The first results of this collaboration are presented in this paper.

2. SPECIFICATIONS

The specifications for the camera were a unique combination of technical and political requirements. Arms control inspections are inherently intrusive operations. They require the presence of inspectors within some of the most highly

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sensitive facilities of a country. As a result, one would like to minimize the time spent on any given inspection. Therefore, the first requirement was that the camera be highly efficient, able to obtain a usable image from a significant mass of plutonium in less than fifteen minutes. This is also consistent with the time required for measurements of the other two defining characteristics of fissile materials and establishes an inspection throughput of about four containers an hour.

The second important requirement concerns camera resolution. As noted above, these inspections are being carried out on highly sensitive components. In 1994, the technical experts agreeed on a set of general shapes that would be indicative of a weapons component. The main point of the shape measurement is to rule out point sources, cans of plutonium oxide, and the like. Very early in the discussions, it was determined that a resolution of one centimeter would be sufficient for this application. Hence the camera was designed to have an approximately 1-cm imaging resolution.

A third requirement is driven by the fact that arms control inspections are not laboratory operations, but are often carried out under remarkably harsh conditions. The camera was designed to be transported to forward weapons storage areas over rough roads and to be operable in the wide variety of weather conditions that could be met in Siberia (or its comparable U.S. match, northern North Dakota). A summary of the camera specifications, taken from the original design document, is presented in Table 1.

3. RESULTS

The design of the camera was carried out under a contract between LLNL and RIPT. After several iterations of the design concept, it was decided that a camera based on the Anger approach would be best suited for this application. The camera would feature a lead honeycomb collimator backed up by a 312-mm, 1/2-in. NaI fluor thickness. This fluor was best suited for measuring the prominent plutonium gamma rays in the 375- to 414-keV region of the spectrum. The fluor would then be viewed by a two-dimensional (2-D) array of photomultiplier detectors. Position information would be obtained using an electronic system developed by RIPT for test applications. The photo tubes were constructed and balanced in the RIPT phototube facility. RIPT also developed the custom software for analyzing the data from the camera.

Following the acceptance of the final camera design, a second contract was developed for the construction of the camera. Construction began in the fall of 1996 and the final acceptance tests were conducted at the RIPT Moscow facility in March of 1998. The camera met or exceeded all of the design criteria listed in Table 1.

The completed camera and power supply system are shown in Figure 1. Information from the camera is read out using a standard PC. The computer also determines the energy region of interest, and is capable of storing position information for a number of different energy regions at the same time. A side view of the camera, showing the collimator array, is given in Figure 2. Figure 3 gives a view of the fluor with the collimator removed. If one looks closely at Figure 3, the location of the 36-phototube array may be seen.

3.1 Energy measurements

Figure 4 shows the results of a measurement of the energy spectrum from the 661-keV ^{137}Cs gamma ray. Three regions have been selected in this spectrum: the 661-keV photopeak, the cesium Compton edge, and the low energy noise peak. Images of all three regions can be collected simultaneously. The region of the Compton edge can be particularly useful for imaging extended sources where internal scattering can have an important effect on the escaping energy spectrum.

3.2 Position results

The first tests of the camera were carried out using point sources and arrays of point sources of both ^{137}Cs and ^{57}Co. Figure 5 presents the result from a two-hour count with a single cesium point source. The software with the camera allows one to view cuts along any straight line through the data. Analysis of this data indicates a resolution of somewhat less than 1 cm. The detector-to-source distance for this measurement was 10 cm, approximately the distance that would be used in an inspection regime. An interesting artifact in the figure is the "star" pattern, with the rays of the star along the lines of the thinnest material in the honeycomb. This pattern is presumably caused by Compton scattering within the collimator, which allows the gamma rays to then reach the fluor along the lines of least material. For count times of interest in inspections, this artifact has a minor effect on the data.

Figure 6 shows the image from an array of five ^{137} Cs sources along with a cut through the center of the array. Note that the cuts through the data are not restricted to horizontal or vertical lines but may be made at any angle. Figure 7 displays a three-dimensional (3-D) view of the results from a single ^{57} Co source. Also shown is a 3-D spectrum with the image from the lower energy gamma rays subtracted from the full energy peak.

Although large plutonium pieces are not available at RIPT, an attempt was made to image a 3-D object. A high intensity ^{137}Cs source was placed at the center of a steel sphere approximately 7.5 cm in diameter. The image of this assembly was taken in the region of 350–450 keV, corresponding to the Compton edge of the gamma ray distribution. The image of this radiator agreed well with the external dimensions of the steel sphere. The image also displayed nonuniformities that agree with calculations of the asymmetry of radiation in certain energy regions from a spherical surface.

It had been hoped that the camera could be to used measure extended plutonium sources at several demonstrations that were to take place during the summer of 1998. Unfortunately, political considerations have so far prevented those demonstrations from happening. The camera is currently being shipped to LLNL, where we will be able to determine its performance on actual items of interest in arms control inspections.

3.3 Operational results

The camera system was tested against the criteria listed in Table 1. Performance before and after being subjected to the environments detailed in the table was essentially identical. Thus it has been confirmed that the camera can be transported by air or truck for unlimited distances under rigurous climatic conditions with no effect on its performance.

4. ACKNOWLEDGMENTS

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Table 1. Design requirements

- Provide search, detection, and localization of weapons-grade plutonium parts in sealed containers.
  - Tuned for radiation the 375 to 415 keV region
- Provide spatial resolution of approximately 1 cm.
- Emanation protection according to the standards for industrial purpose
- Survivability and resistance to external effects
  - Operating temperatures from –10 to +35°C
  - Limiting temperature from –15 to +40°C
  - Operating humidity to 95% at 25°C
  - Survive 10,000 km transport in regular packing
  - Survive 10 shocks of 2 g in regular packing

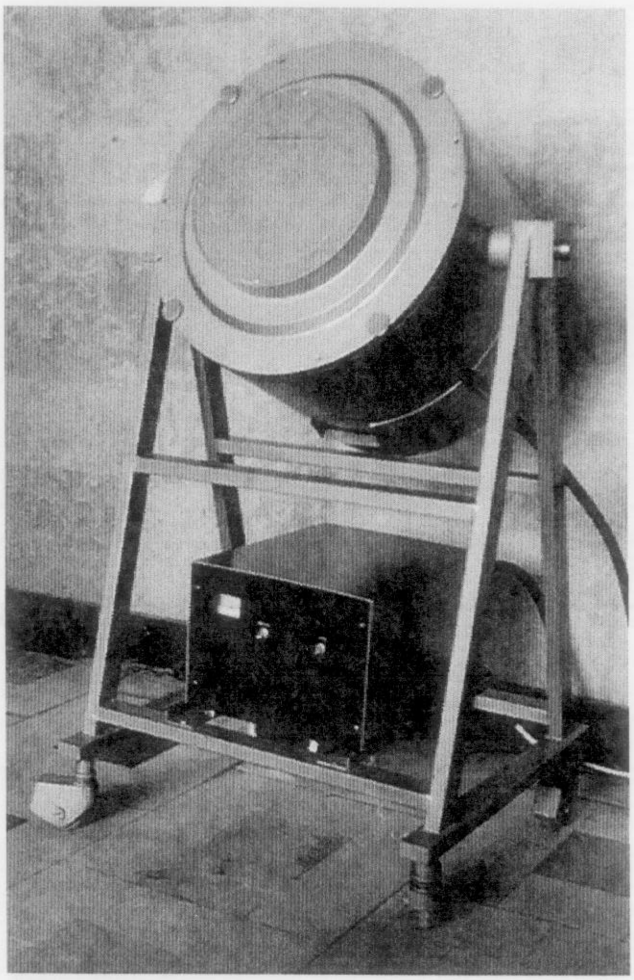

Figure 1

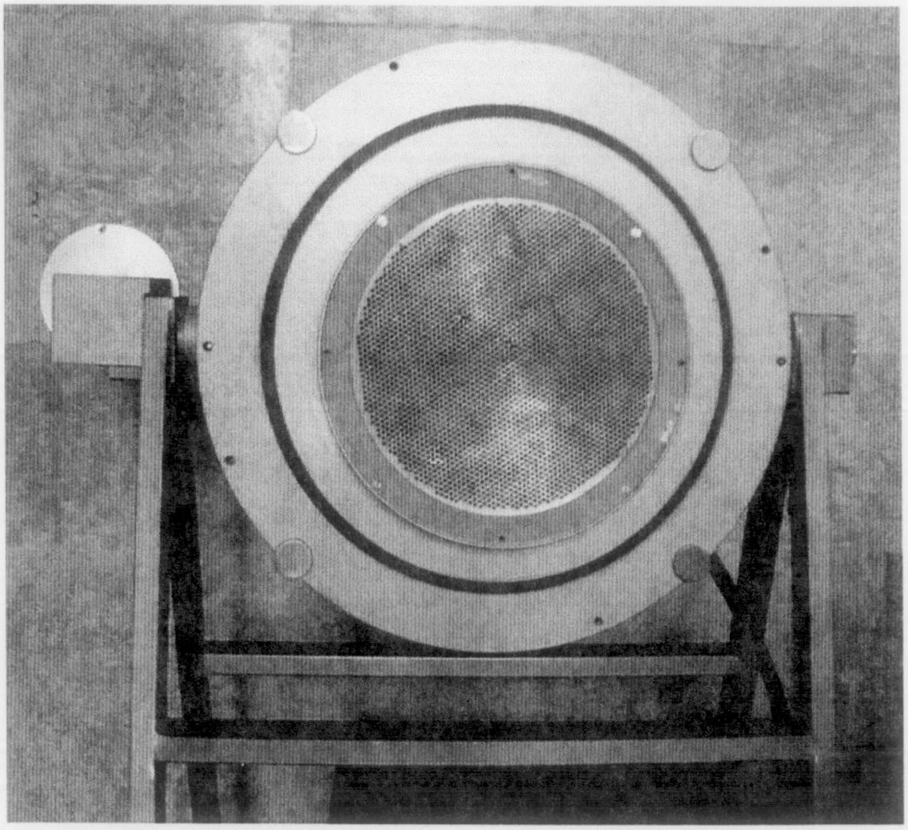
Figure 2

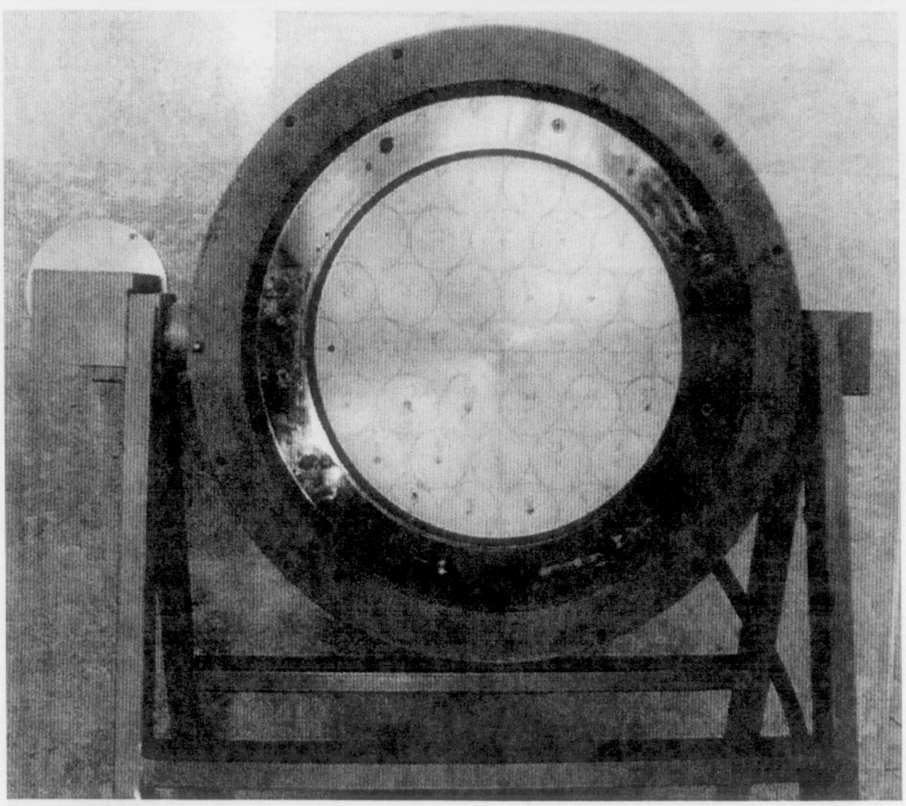

Figure 3

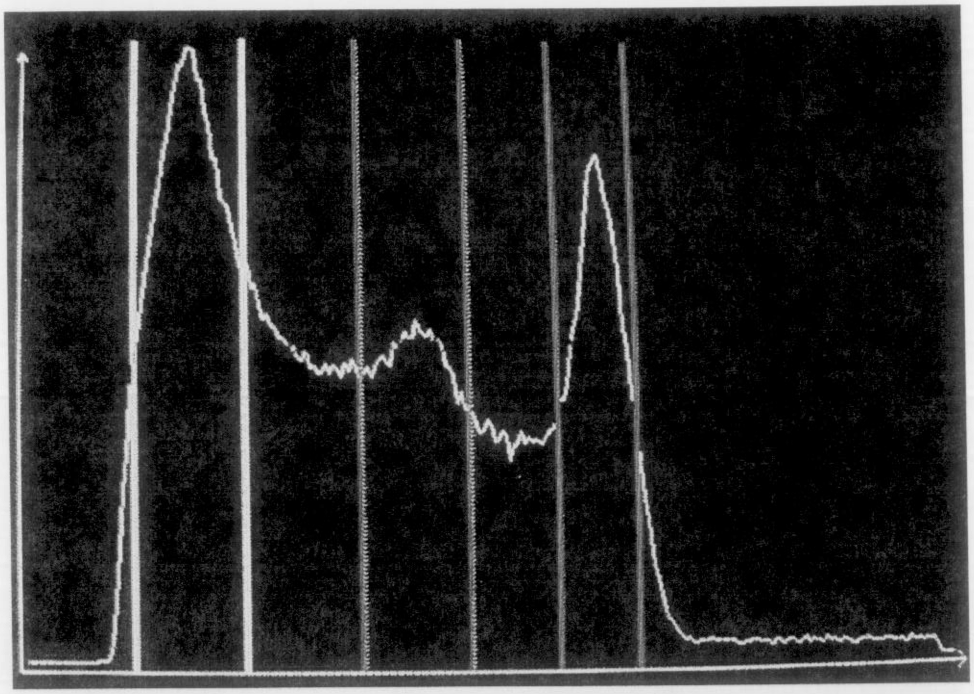

Figure 4

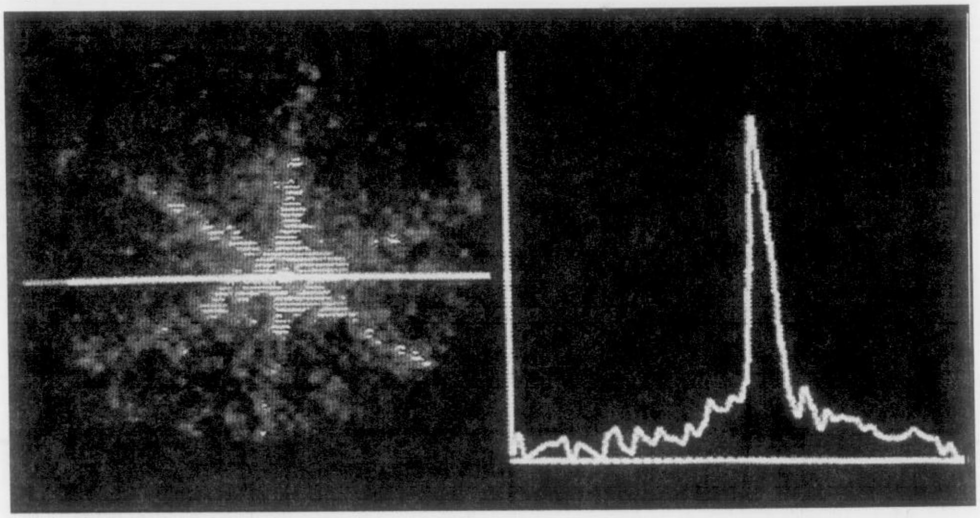

Figure 5

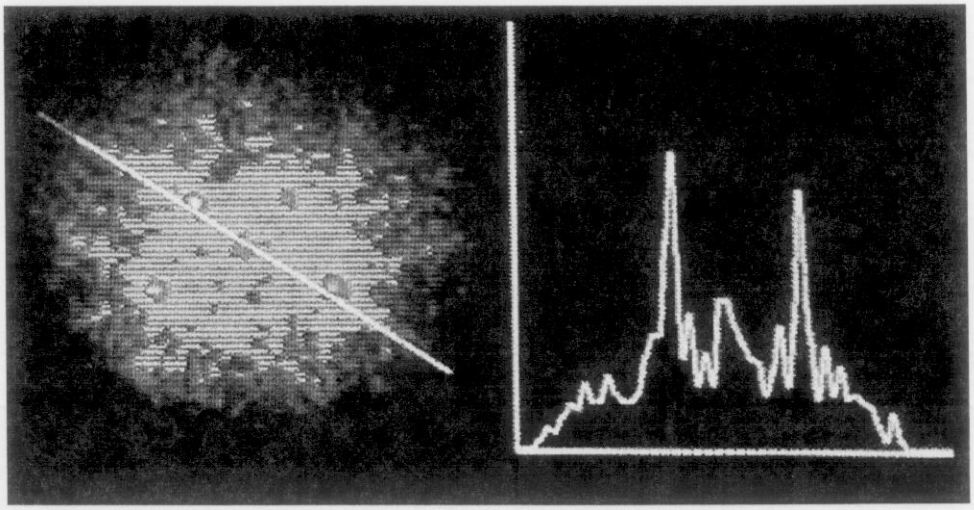

Figure 6

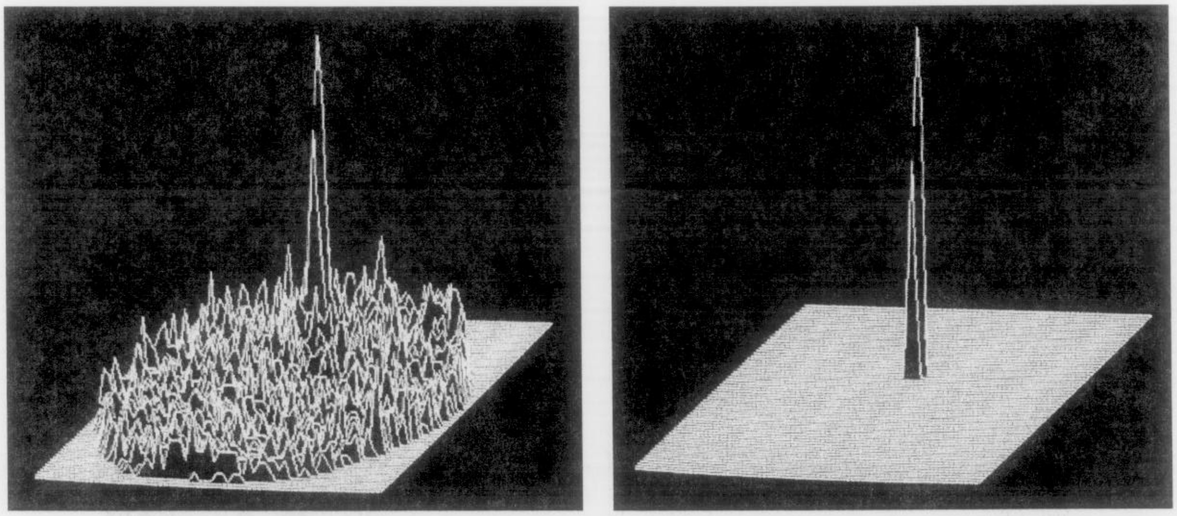

Figure 7