

## LOW-COST X-RAY INSPECTION OF HIGHLY ATTENUATING MATERIALS

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### INTRODUCTION

As a result of an arms reduction treaty between the United States and the Russian Federation, both countries will each be storing over 40,000 containers of plutonium. To help detect any deterioration of the containers and prevent leakage, we are designing a digital radiography and computed tomography system capable of handling this volume reliably, efficiently, and at a lower cost.

The materials to be stored have very high x-ray attenuations, and, in the past, were inspected using 1- to 24-MV x-ray sources. Our inspection system, however, uses a new scintillating (Lockheed) glass [1-3] and an integrating CCD camera [4]. Preliminary experiments show that this will permit the use of a 450-kV x-ray source. This low-energy system will cost much less than others designed to use a higher-energy x-ray source because it will require a less expensive source, less shielding, and less floor space. Furthermore, we can achieve a tenfold improvement in spatial resolution by using our knowledge of the point-spread function of the x-ray imaging system and a least-squares fitting technique.

Other novel features of this inspection system include (1) using a personal computer to automatically extract thickness and density measurements and (2) a database to detect anomalies in the stored materials quickly and easily. Many of the techniques described here can be used in other inspection systems.

## SYSTEM REQUIREMENTS

Our system will inspect all containers before storage to assess the condition of the material and then inspect approximately 1% of the stored containers each year to ensure that the material is not deteriorating. The system is designed to run 24 hours per day, 7 days per week, inspecting one container each hour. This gives us the capacity to inspect 4000 containers per year with ample time left for maintenance, upgrades, and more precise inspection of a few containers with unusual conditions.

The treaty requires a 100% physical audit of the containers in the storage vault each time anyone enters the vault or a container is removed. Because of the prohibitive cost and time required for a physical audit, we are planning to build an x-ray-transparent window into the vault and place the x-ray source and detector outside. The inspection system must be compatible with an automated robotic handling system, which is being designed elsewhere.

The material to be stored will include raw plutonium, plutonium oxide (a powder), and plutonium "pits" from dismantled hydrogen bombs. A pit is a thin shell of plutonium that creates the nuclear explosion by undergoing a nuclear reaction. Surrounding the plutonium shell, the pit has a tamper shell of beryllium, stainless steel, or uranium, and an outer shell of stainless steel. The stainless steel shell provides a safe and stable environment to protect and contain the plutonium. The outer diameter of the stainless steel shell is less than 15 inches.

The storage containers are designed to prevent the deterioration of the plutonium, i.e., the formation of plutonium hydrides and oxides. Therefore, the existence of these compounds will alert us that the containers are failing in some way. These compounds are also indicators that pyrophoric plutonium compounds may be forming. Because it is extremely important to avoid fires in the storage vault and the spread of fine plutonium powders formed during a fire, the detection of the hydrides and oxides is crucial. Fortunately, the hydrides and oxides are very easy to detect radiographically because they are powders with about 60% the density of plutonium.

The system we describe here will be able to measure the thicknesses and densities of all the shells in the pit and the storage container wall at selected locations. It will also be able to measure the total volume of raw plutonium and plutonium oxide stored in these containers. For the remainder of this description, we describe only the pit inspection features. However, many of the pit inspection features can also be used for the solids and powders.

## SYSTEM DESCRIPTION

We are using scintillating glass coupled to an integrating CCD camera to make a digital x-ray imaging system. By using least-squares fitting, we will measure the thickness and position of the edges of the shells to an accuracy of one-tenth of a pixel. The output from the fitting process goes into a data base. Personal computers will analyze the data base to detect anomalies in the stored materials.

### Low-Energy Digital Imaging

Both Savannah River and Livermore are using scintillating glass and integrating CCD cameras to make digital x-ray images. In some instances, experienced radiographers have claimed that these images are as good as film radiographs. Initial experiments have shown that highly attenuating materials such as plutonium pits are imaged at 450 kV with these systems. This is an amazing result, considering that, in the past, we have typically used 1- to 24-MV x-ray sources to image pits. Plutonium has the density and x-ray attenuation of lead, a material commonly used for x-ray shielding.

Good images of the pit can be obtained at 450 kV because the scintillating glass is a more efficient x-ray detector than film, and we can integrate the image for up to 30 seconds with relatively inexpensive CCD cameras. Although the plutonium absorbs most of the x-ray photons from the source, a few photons pass through the pits. By integrating the image for 30 seconds, we obtain an image with good signal-to-noise characteristics. We have also seen some good results using gadolinium screens [5]. These screens produce more light but have poorer spatial resolution than the glass. Nevertheless, we plan a side-by-side comparison of these two materials to determine which one is best for this application.

By using our knowledge of the point-spread function of the x-ray imaging system, we can apply a least-squares fit to the edges of cylindrically symmetric objects to give a tenfold improvement in the measurement of the location of edges. Therefore, we will be able to measure the location and thickness of all the shells in a pit to better than one-tenth of a pixel. We have tested the concept of this least-square fitting technique by digitizing a film radiograph of a pit. In this test we located the edge and thickness of the pit with one-tenth pixel accuracy. This translates into 25-micrometer (0.001-inch) accuracy for the digital images.

### The Inspection Process

We plan to make five views of each container, each view rotated by a 30-degree increment. In each view, we will measure the radius (location), thickness, and density of the material at 90 evenly spaced locations. From this information we create a data base detailing the condition of the container and its contents at 450 locations.

By using the data base, personal computers can quickly detect anomalies. Values from a new inspection will be subtracted from the values obtained in the previous

inspection. Large differences will indicate a change in the material. Data from the first inspection will be subtracted from the values in the design drawings.

For more detailed inspections, a high-resolution computed tomography scan mode is also available. In this mode, we collect data at more angles and extract more measurements of the shells. Then we reconstruct two-dimensional images of slices through the pit and fully three-dimensional volumetric images of the entire pit. These images are far better than those from any film imaging system.

#### Advantages of this System

Using a 450-kV source saves money for a new installation. The source is less expensive than the 1- to 24-MV sources we would have used previously and requires less floor space and less shielding. Higher-energy x-ray machines require a larger inspection bay to reduce the number of x-rays that scatter off the walls and stop in the detector. Less floor space means we save on construction costs. Less shielding means we save on the costs of the shielding and the foundation to support it.

The all-digital system we propose would eliminate film processing and the chemical waste from traditional film radiography techniques. For the first inspection of each container, it would save \$6 million in x-ray film costs and also \$8 million in labor costs, due to the reduction in time needed for film processing and pit evaluation.

The digital data base improves the evaluation by removing the subjectivity of a human interpreter. The reproducibility of the inspection system can be verified periodically by inspecting a known standard. Furthermore, the data base provides data for a variety of statistical studies, and the results of the inspection are easily interpreted by people from a wide variety of backgrounds.

#### SUMMARY

New techniques enable low-cost x-ray inspection of plutonium in storage and other materials with high x-ray attenuation. The detector, consisting of scintillating glass and an integrating CCD camera, permits the use of a 450-kV x-ray source rather than the 1- to 24-MV sources typically used. This lower-energy source saves money in the construction of the x-ray facility. We use least-square fitting to extract the dimensions of the stored material with a precision of about one-tenth of a pixel in the x-ray image. The output is stored as a digital data base. Personal computers use the data base to detect anomalies quickly and easily.

#### REFERENCES

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