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Portable Radiography for Arms Control Verification

Los Alamos

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Portable Radiography for Arms Control Verification

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PORTABLE RADIOGRAPHY FOR ARMS CONTROL VERIFICATION

by
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ABSTRACT

A series of radiographs were made to demonstrate the advantages and limitations of radiographic techniques for inspecting objects of interest to arms control verification. Two objects (a Sgt. York artillery round and an SS-25 rocket mock-up) were radiographed with a ^{60}Co (1.1 MeV) isotope and a 150-pkV x-ray machine. Two types of detectors were used for all radio- graphs: fast industrial x-ray film with fluorescent screens and the new storage phosphor technology manufactured by Eastman Kodak. The resulting images are analyzed for their suitability in performing portal inspections for arms control verification.

I. INTRODUCTION

The purpose of this exercise was to demonstrate the capability of portable radiographic systems to perform field inspections for arms control purposes. For the purposes of this report, portable means that two people driving a truck can set up their equipment, make the radiographic exposure, and generate a hard-copy image in under 2 h. No assumptions are made concerning services (water and power); the system is self-contained. The only assumption is that the truck can be driven to within a few meters of the inspection site. The demonstration stopped at generating an image. Moving the image (electronically or otherwise) to another site for storage and/or interpretation was also not performed.

II. EQUIPMENT

The equipment for an inspection of this type includes the following:

- X-ray source -- 150-pkV Golden x-ray machine and 235-Ci ^{60}Co source
- X-ray detectors -- Du Pont NDT 57 film with fluorescent screens and Eastman Kodak storage phosphor (SP) system
- Darkroom for handling both the film and SP screens
- Truck with power and water for transporting and supporting the radiographic systems

A. X-ray Sources

The two sources used in this demonstration were chosen for their energy range, portability, and availability; other sources, both isotopic and x-ray, could be used.

1. Golden X-ray Machine. The Golden x-ray machine is a small, 10-lb, pulsed x-ray machine that emits pulses with a maximum energy of 150 pkV. For this inspection, the fact that the machine is pulsed is immaterial; the system's portability was the primary factor in choosing it.

Figure 1 illustrates the portability of the complete Golden system: all of the equipment is contained in a single suitcase. Figure 2 illustrates the equipment set up and ready to make a radiograph. The box on the tripod contains the x-ray tube and the power supply. Only two cables (110-V power and a control cable) connect to the box. The exposure is controlled by thumbwheel switches that specify the number of pulses. The equipment can also be operated with an optional battery pack, thus eliminating the need for ac power.

The Golden machine has a low x-ray intensity output (0.28 mrad/pulse at 1 m) that, when coupled with the low energy (150 keV), requires a very sensitive detector.

Fig. 1. The 150-pkV Golden x-ray machine.

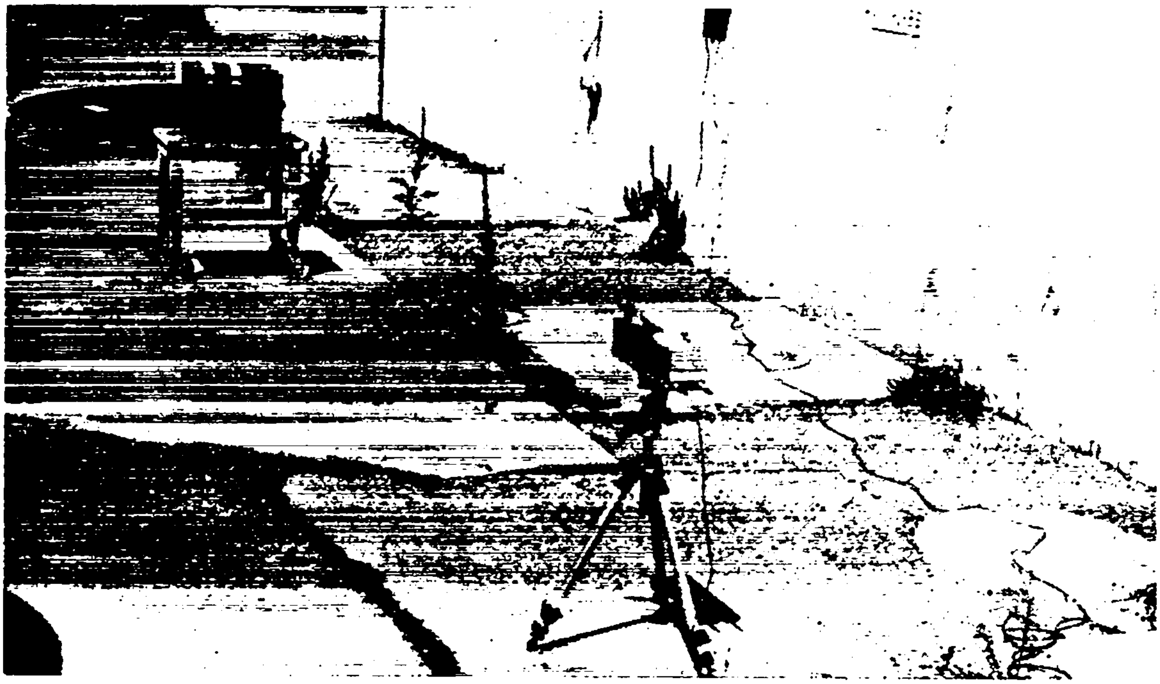

Fig. 2. The 150-pkV Golden x-ray system in position.

2. ^{60}Co Source. At the other energy extreme, the second radiographic source was a 235-Ci ^{60}Co isotope, which is stored in a 500-lb depleted-uranium pig that can be rolled by one person. However, moving the source from the truck to the ground requires a fork lift, hydraulic lift gate or crane. One significant advantage of an isotopic source is that no electrical power is required; the source is cranked out and returned to the pig manually. When these exposures were taken, the source had an average energy of ~ 1.2 MeV, with an intensity of 5.9 rad/min at 1 m. Figure 3 shows the cables being hooked up to the pig prior to an exposure, and Fig. 4 illustrates the pig connected to the source holder/collimator. One cable connects the pig to the source holder/collimator while the other cable allows the operator to crank the source out (see Fig. 5).

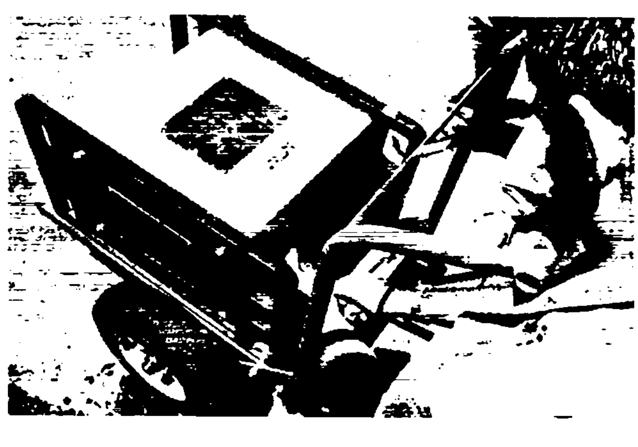

Fig. 3. Cables being hooked to the ^{60}Co source.

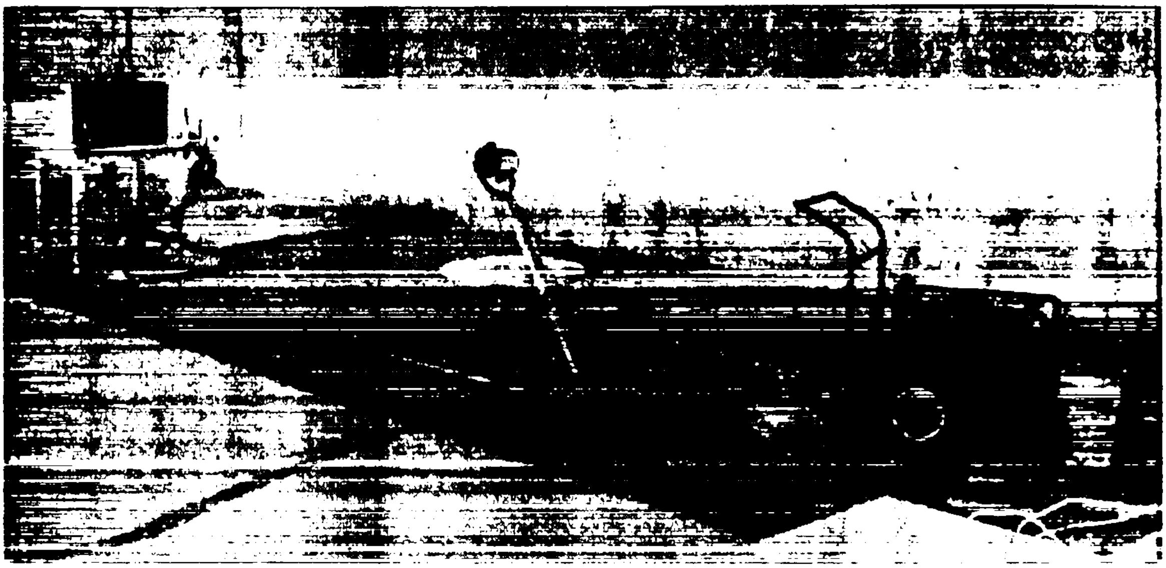

Fig. 4. The ^{60}Co source pig and collimator.

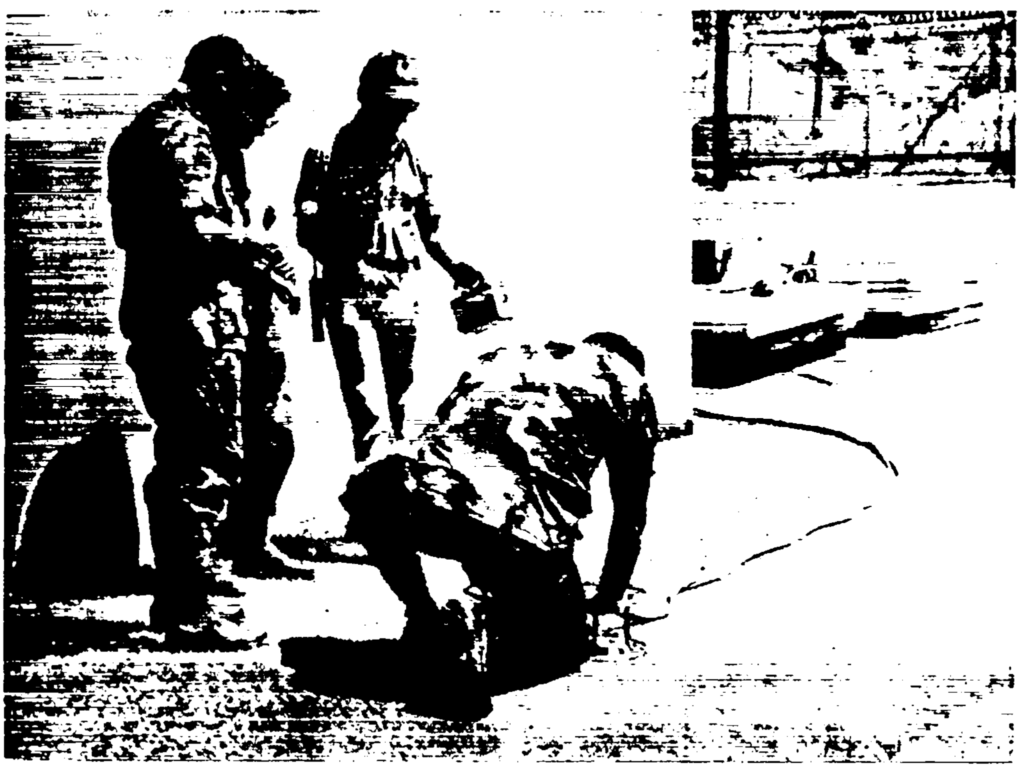

Fig. 5. Cranking out the ^{60}Co source.

B. Detectors

Two types of detectors were used: conventional film and storage phosphor (SP). With conventional medical or industrial film, the light emitted from a fluorescent screen exposes the radiographic film when an x-ray photon is absorbed. The SP is basically a fluorescent screen in which the absorbed energy is stored for some minutes or hours in a metastable state. This energy is then read out in a separate operation and converted directly to digital form.

1. **Film Detector.** For this demonstration, we chose Du Pont type 57 radiographic film and combined it with NDT9 fluorescent screens. While this is a very fast combination, faster film/screen combinations are available. In fact, with appropriate choices of films and screens, a speed range covering 3 orders of magnitude can be achieved.

2. **Storage Phosphor Detector.** The SP detector consists of an x-ray-sensitive phosphor that is excited into a metastable state (which has a lifetime that is measured in hours) when an x-ray photon is absorbed. When the phosphor is exposed to a focused laser beam, the fluorescence from the metastable state is detected and used as the output signal. The laser beam is scanned over the fluor while the fluorescent light is digitized to build up the image. The fluor from the SP detector can then be erased and used again.

Table I lists some of the important operating parameters of the SP system.

Table I. Storage phosphor operating parameters.

Parameter	Specification
Read-out laser	10-mW HeNe laser
Laser spot size	100 μm
Sampling interval	100 μm
Image size	14 x 17 in. (3556 x 4318 pixels)
Scan time	5 min
Analog-to-digital converter depth	12 bits
Fluor decay times	2.5 and 200 h
Optimum erase wavelength	450 nm

The principle advantages of the SP detector are its large dynamic range (5 orders of magnitude) and its ability to digitize the image directly. Although conventional radiographic film has an intrinsically large dynamic range, in practice, the dynamic range is limited to 2+ orders of magnitude by the limitations of the human eye and microdensitometers. If convenient techniques were available for extracting the image when the optical density is 4.0, the increased dynamic range of films such as Kodak types AA and M could be used.

Both detectors require a darkroom. The truck shown in Fig. 6 has a darkroom built into the back, which is large enough to fit either a Fuji automatic film processor or the SP read-out system. However, we did not use the truck's darkroom in these experiments, but opted, instead, to use our fixed laboratories.

III. EXPOSURES

As test objects to demonstrate the radiographic capabilities, we chose a mockup of an SS-25 rocket inside its canister and a dummy Sgt. York round. Both objects were radiographed with each detector and x-ray source. The exposure parameters for each source and object were the same for both detectors. The four source and object combinations with their exposure parameters were the following:

- Golden radiograph of Sgt. York--300 pulses at 4 m (5.25 mrad)
- Cobalt radiograph of Sgt. York--15 Ci • min at 4 m
- Golden radiograph of rocket--600 pulses at 3 m (18.7 mrad)
- Cobalt radiograph of rocket--25 Ci • min at 3 m

The storage phosphor images were digitized with 100-µm pixels and then reproduced on the Lasertechnic printer with an effective pixel size of 400 µm. The film images were digitized on a Du Pont scanner with a 70-µm pixel size. The original images were then averaged with a 5- by 5-pixel kernel to produce a Lasertechnic picture with an effective pixel size of 350 um.

Figures 7 and 8 are film radiographs of the Sgt. York round taken with the 150-pkV Golden machine and the ^{60}Co source, respectively. Figures 9 and 10 are the SP images of the same object with the same sources.

Figures 11 and 12 are the film radiographs of the rocket mockup taken with the Golden machine and ^{60}Co source. Figures 13 and 14 are equivalent radiographs using the SP detector.

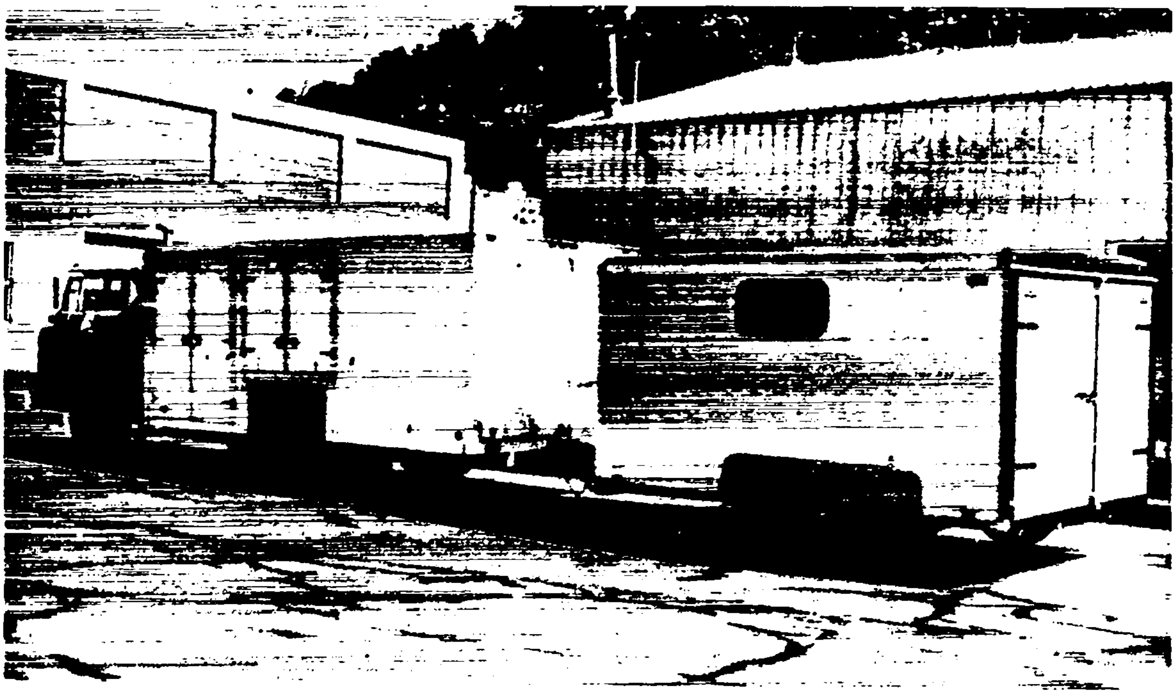

Fig. 6. Truck and trailer for transporting the radiographic system.

IV. COMPARISON OF FILM AND SP IMAGES

A comparison of the radiographic images of the Sgt. York round (Figs. 7 and 8) shows that the higher energy of the ^{60}Co source produces an image with less contrast but with a higher dynamic range than the 150-pkV energy of the Golden machine. The only detail visible in the Golden radiographs of the rocket mockup is the insulation installed in the wall of the canister (see Figs. 11 and 13). In both figures, the edge of the rocket case itself is visible but nothing inside shows. The streaking artifacts that are visible inside the rocket case in Fig. 11 are probably caused by incomplete signal normalization on the Du Pont scanner. There is absolutely no evidence of any image in this region on the original radiograph, and we have probably amplified the image to the point where we are seeing incomplete corrections for sensor variations. The lower energy of the Golden machine cannot penetrate the Sgt. York round (see Fig. 7), while the cobalt radiograph can detect the void in the epoxy filling at the shoulder of the case and the rebar's spiral ridges (see Fig. 8).

The SP images are generally lower quality than the film images, particularly at the 1.2-MeV energy of the cobalt source. A comparison of Fig. 10 with Fig. 9 shows that the SP images are also noisier and have less contrast than equivalent film images because the noise and contrast characteristics of film are better than those

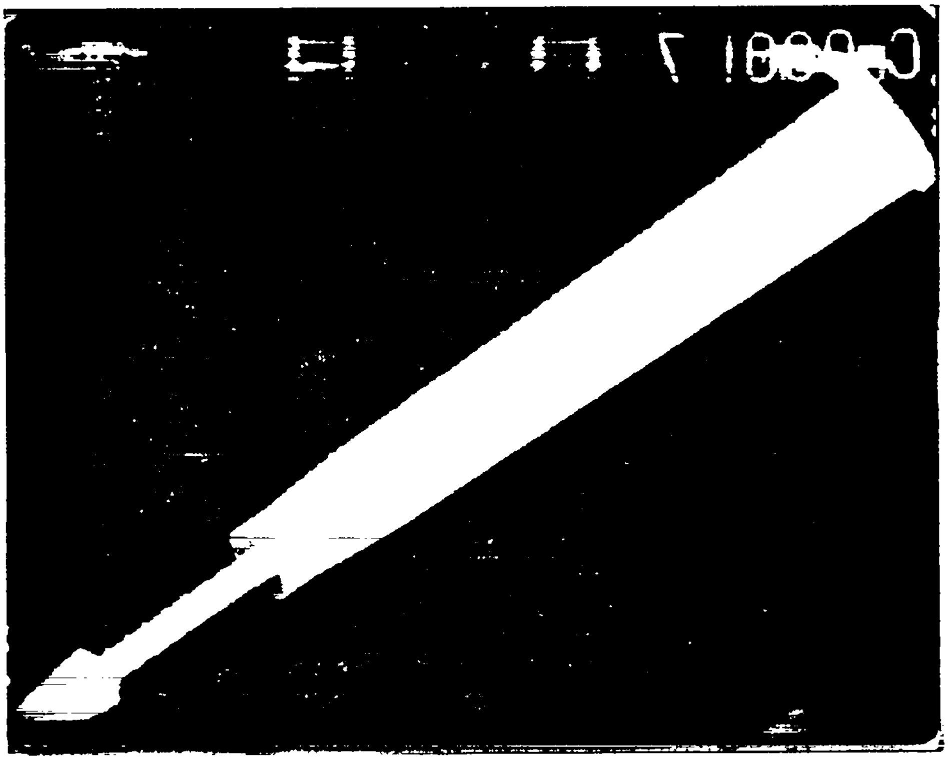

Fig. 7. The 150-pkV Golden radiograph of the Sgt. York round using Du Pont film.

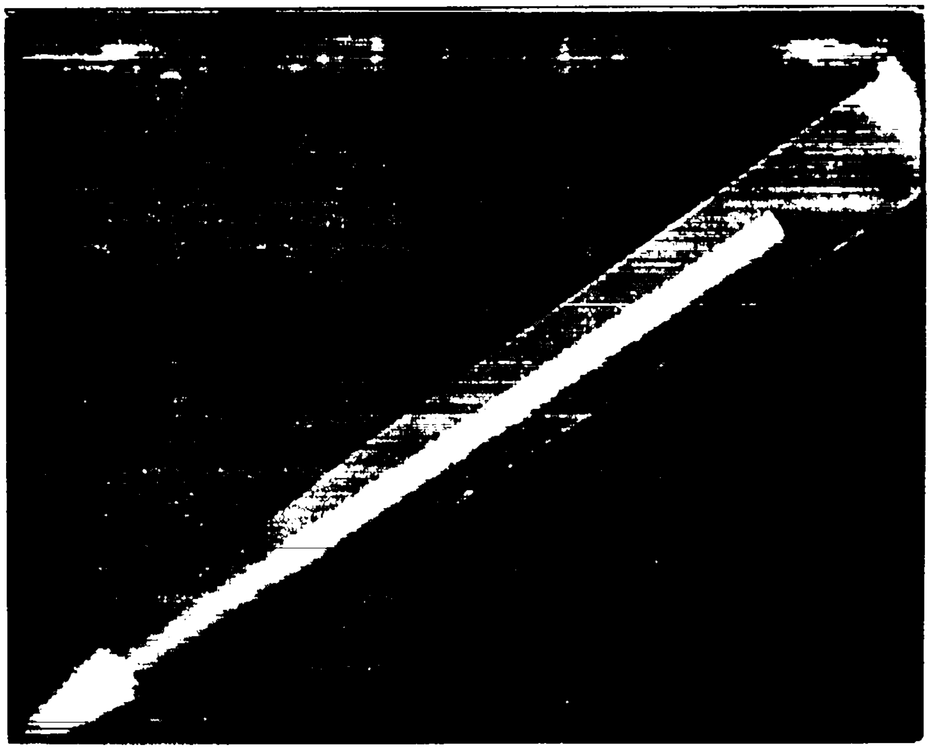

Fig. 8. The ^{60}Co radiograph of the Sgt. York round using Du Pont film.

of the SP at high film doses. If the radiation dose were low for operational or other reasons, the image quality of the film and SP images would be more equivalent. Note that the SP image of the Sgt. York round using the cobalt source does not have enough contrast to depict the spiral ridges on the central rebar while this detail is obvious in the film image (see Fig. 10).

As a measure of the relative ability of various x-ray or gamma-ray sources to penetrate objects, consider the thickness of steel that would transmit 13% of the incident radiation at three energies: 150 pkV, 300 pkV, and 1 MeV. (The 13% number is simply the percent transmitted when the product of the attenuation coefficient and the thickness of the object is two.) The thicknesses are 0.7, 1.8, and 4.25 cm at 150 pkV, 300 pkV, and 1 MeV, respectively. The two lower energies are produced by common x-ray machines; the 1 MeV energy approximates that produced by the cobalt source. These thicknesses should not be interpreted as absolute thickness limits, only as relative penetration numbers. For instance, a 300-pkV machine will produce roughly the same contrast through twice as much material as the 150-pkV machine. If the source is a ^{60}Co isotope, you can have at least double the material thickness and still achieve the same image contrast as the 300-pkV machine. These estimates are crude because they ignore the relative contribution that the scattering cross section makes toward the beam attenuation. In general, as the x-ray energy increases, the scattering increases relative to the absorption. This causes more scattered (non-imaging) radiation to reach the detector, thereby decreasing the contrast. This effect is particularly noticeable with the cobalt source.

In general, at low energies (150 pkV), objects with an equivalent thickness of < 1 cm of steel will be imaged with good contrast. As the thickness increases to 2 cm or more, the contrast decreases dramatically, producing a shadowy outline of the object. If the x-ray energy increases to about 300 pkV, the thickness values in the previous sentence are more or less doubled. If the x-ray source is replaced with the cobalt source, the thickness values can roughly be doubled again.

The preceding paragraphs discuss relative beam transmission and how it affects image contrast. The absolute transmission of the x-ray beam through the object in units of fluence (photons/mm^2) determines the detector sensitivity that is required to make a useful image. With an appropriate choice of detector, a usable image can be obtained over 3 (conventional film) to 5 (SP) orders of magnitude of the transmitted radiation fluence.

Good radiographic practice generally is to get the maximum x-ray fluence on the detector within the operational constraints of the inspection procedure. As the fluence increases, the appropriate detector generally has less noise and more resolution. At very low fluences (10 000 photons/ mm^2), the image is fundamentally limited by photon statistics, and even the most sensitive detector produces a poor image.

Fig. 9. The 150-pkV Golden radiograph of the Sgt. York round using SP.

Fig. 10. The ^{60}Co radiograph of the Sgt. York round using SP.

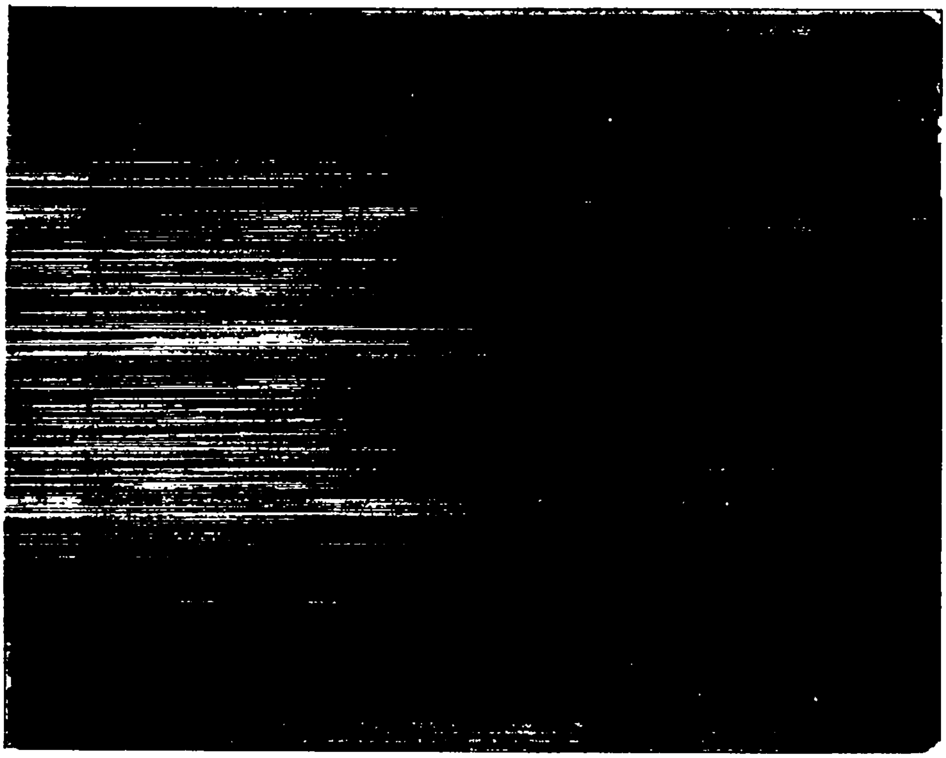

Fig. 11. Golden radiograph of rocket mockup using Du Pont film.

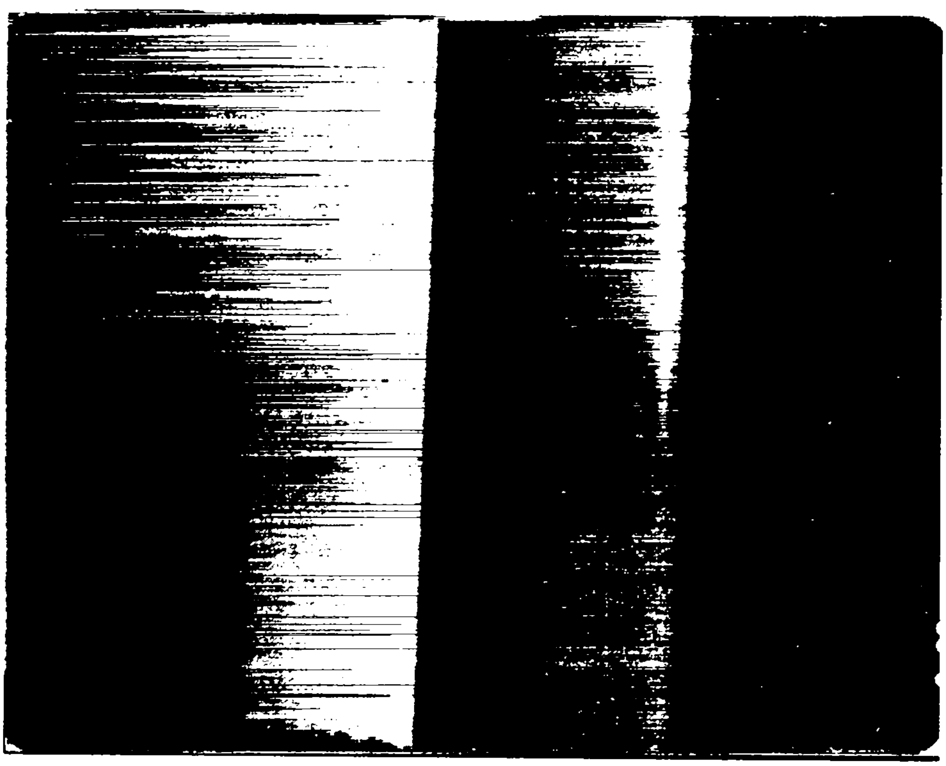

Fig. 12. Cobalt radiograph of rocket mockup using Du Pont film.

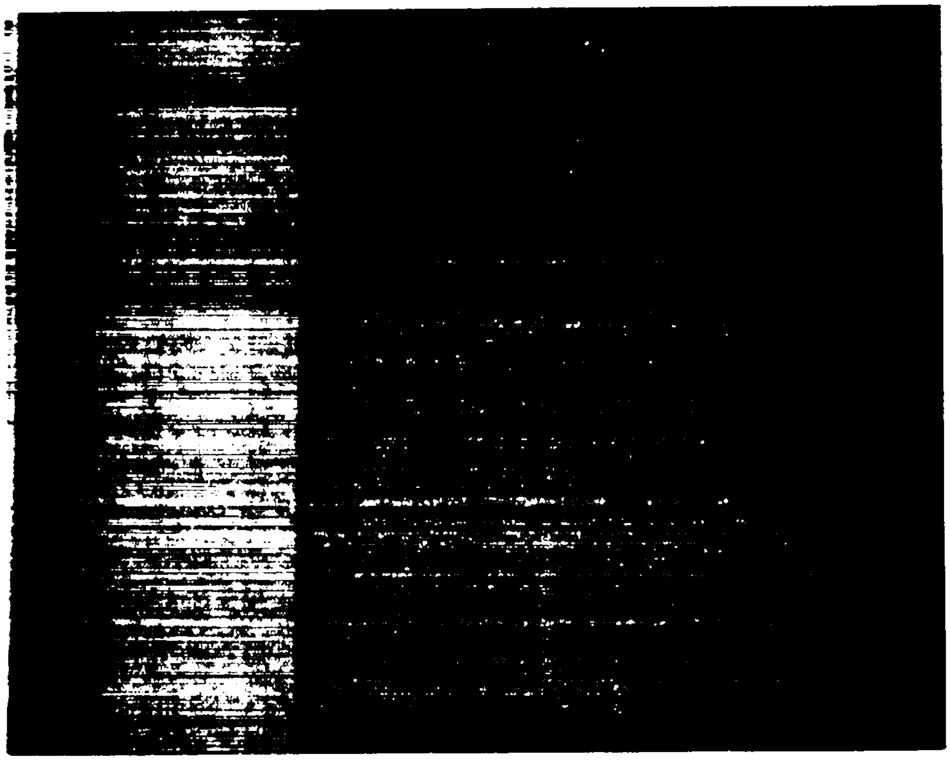

Fig. 13. Golden radiograph of rocket mockup using SP.

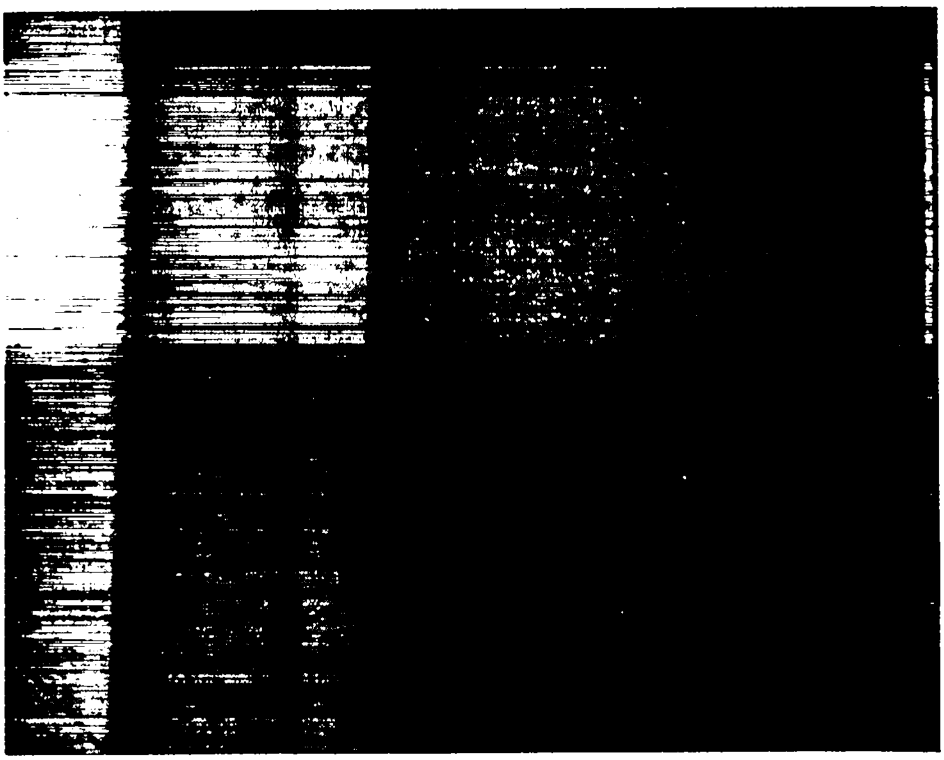

Fig. 14. Cobalt radiograph of rocket mockup using SP.

In an earlier study,[1] we compared SP technology with conventional film/screens and drew several conclusions.

(1) Storage phosphor images can be obtained with much higher doses than conventional film.

(2) At very low doses, a conventional film image that has been contrast-stretched is roughly equivalent to or slightly poorer than an SP image.

(3) When the dose is greater than 50 000 photons/mm^2 but less than the saturation dose for film, the film image is clearly superior. This dose level seems to be independent of photon energy.

While there is some variation, these conclusions are more or less independent of x-ray energy. If there is a trend, conventional film would seem to produce a better image than SP at the same dose as the energy increases.

If the inspection constraints forbid wet chemical processing, the "best" radiograph is not required. Since you only have one chance to get a "good" radiograph, the electronic processing and large dynamic range of SP make it the detector of choice. On the other hand, if you are inspecting a large number of identical parts, can develop a good radiographic technique up front, and can use wet chemical processing, conventional film is probably the best choice. This decision ignores cost factors, which, for the SP processor, can cost as much as 10 times more than the processor for conventional film.

Additional reasons for choosing SP detectors may include (1) if the radiograph must be taken at very low doses, (2) if image quality is secondary, and (3) if a digital image is required immediately. The SP detector produces roughly the same quality image, albeit poor, as conventional film, and the image will already be digitized for the necessary contrast-stretching. This introduces the question: Why take a low-dose image in the first place? I can think of only two reasons: to reduce radiation damage to the object and to reduce the radiation hazard to people. Furthermore, because a low-dose radiograph never produces the best image, it would only be used for very special needs, such as an airport inspection system or treaty verification.

IV. APPLICATION TO TREATY VERIFICATION

The types of x-ray sources used in this study are ideally suited for portable inspection stations, such as a portal inspection applied to treaty-verification problems. As demonstrated in Fig. 1, the 150-pkV Golden machine can be handled by one man and set up in < 15 min. The Golden Company is developing a 300-pkV version of this machine that has the same size tube head, but a different power supply.

Unless there is some reason to use the pulsed or low-dose capability of the Golden machine, there are a number of other commercially available, low-weight x-ray machines that might be more useful. These machines are considerably larger than the Golden, but they can still be handled by two people and set up in < 30 min. The advantages of these machines include their higher x-ray output and their ability to run at all energies up to the maximum, normally 350 pkV; the Golden machines are fixed-energy machines.

By comparison, the ^{60}Co source is considerably bigger and heavier; the storage pig is made of depleted uranium and weighs about 500 lb. The pig can be rolled on wheels but loading and off-loading from a truck requires equipment. Again, for field operations, the source can be set up for operation in under 30 min. However, more care must be taken to ensure personnel safety since the higher energy source literally cannot be turned off. On the other hand, conventional x-ray machines can be turned off, and the lower energy Golden machine requires less shielding. One centimeter of lead around the tube is more than adequate to shield all but the direct beam.

With either SP or conventional film, the largest block of time needed to generate a finished image is in setting up and getting the detector running. In principle, the reader for the SP detector only needs to be turned on and allowed to warm up before operation, but some type of check-out procedure will probably have to be done. Because the image is born as a digital image, some type of display and analysis station must also be provided.

Conventional film processors must also be warmed up to allow the chemicals to come to the proper temperature before processing film. With film, displaying the image simply means putting the film on a light table. However, if any type of image processing is required, the film must be digitized, then displayed and analyzed with the same type of computer system used for the SP system.

The medical and industrial radiography communities interpret radiographs visually on a light table (except for some volume-production operations), which can be a complicated problem, involving the light-table characteristics, observer training, and room illumination. Both the type of interpretation and the purpose of the radiographic program determine the characteristics of the desired image quality. This determination requires the services of a professional radiographer who can provide the expertise necessary to design and operate such a system. The technical options investigated here are potential components for such a system, but the system itself must be designed to meet specific needs.

V. CONCLUSIONS

Using both conventional film and SP detectors, we have demonstrated that portable radiographic systems are capable of inspecting large (rocket casing) and small (artillery round) objects. The image quality and, hence, the amount of information obtained depend heavily on the object being inspected and the radiographic technique.

Designing a radiographic system is a complex problem that depends upon the object to be inspected; operational constraints (portability, inspection rate, costs, etc.); and political considerations (that is, degree of intrusiveness). Without knowing all of these factors, we are necessarily limited to talking in generalities.

ACKNOWLEDGMENTS

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REFERENCE

1. R. A. Morris, "Evaluation of Storage Phosphor Technology," Los Alamos National Laboratory report LA-12033-MS (April 1991).

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