J. L. Cason[1]

Neutron Radiography with ^{252}Cf in Forensic Science

Nuclear methods have been developed and applied in most scientific fields in recent years, including the forensic sciences. One of the newest nuclear techniques is neutron radiography. Although the first radiograph with neutrons was made in 1935, only since the availability of large neutron sources has the experimental technique been developed into an acceptable nondestructive testing method. With the introduction of reactors, neutron radiography made rapid advances. Research with neutron sources such as Pu-Be, Sb-Be, and neutron generators has also aided its development. However, until ^{252}Cf was made available all useful neutron sources were stationary and costly.

A research program at Battelle-Northwest sponsored by the Division of Isotopes Development has led to the development of a neutron camera using ^{252}Cf. The camera is portable, nearly maintenance free, and highly efficient for neutron radiography. With the development of a portable, high flux neutron source the user need no longer depend on costly reactors or complex neutron generators.

Neutrons and Matter

Neutron radiography, like X or gamma ray radiography, provides for the internal interrogation of an object with penetrating radiation. The image of the attenuated radiation is recorded and furnishes the information needed for evaluation of the object. As expected, image characteristics depend upon the attenuation of the radiation as it passes through the object, as well as on the imaging method. When comparing neutron to X ray radiographs emphasis should be placed on the relative neutron absorption of materials as compared to X ray absorption. This basic difference in absorption characteristics makes neutron radiography a unique and useful technique.

The attenuation of X rays by various materials is largely mass dependent. The more dense the material, the smaller the amount of radiation that can penetrate the object. The attenuation factor is known as the mass absorption for X rays, and a plot of this parameter versus the atomic number is given in Fig. 1. The absorption of neutrons is a combination of production events (absorption) and neutron scatter. Both processes remove neutrons from the incident neutron beam and hence contribute to absorption. Both factors are considered in the total cross section for the material. As can be seen from Fig. 1, the high scatter of neutrons by light elements seems to be particularly advantageous, as is the ability to discriminate between several materials which have similar X ray absorption coefficients. Examples showing the difference in the distinguishing characteristics of photons and neutrons are given in Figs. 2*a* and 2*b*.

Received for publication 20 Feb. 1971; accepted for publication 23 Sept. 1971.

[1] Battelle-Northwest, Richland, Wash.; presently, Gamma Industries, Inc., Baton Rouge, La.

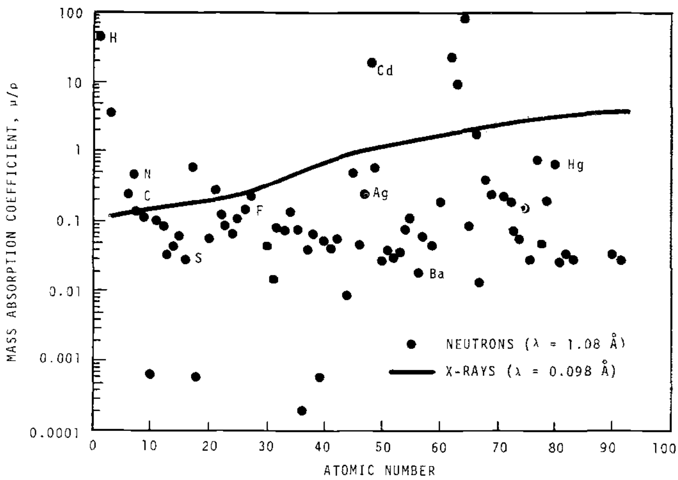

FIG. 1—*Comparison of thermal neutrons and X ray absorption for various elements.*

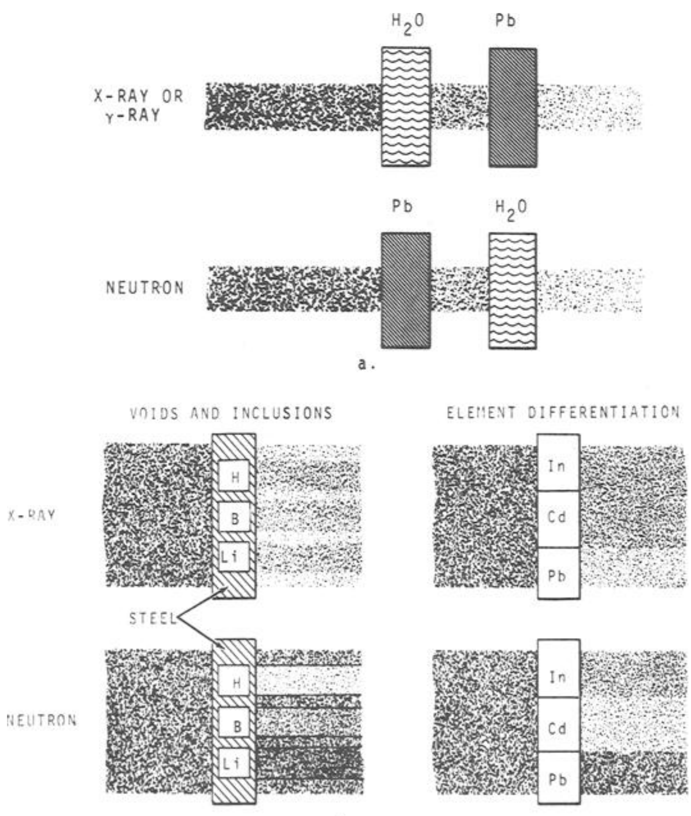

FIG. 2—*Graphic comparison of X ray and neutron radiography.*

Within the concept of neutron radiography there are two major classifications, differentiated according to their neutron energy. These are thermal and fast neutrons. No direct corollary can be made to X ray radiography; here increasing energy mainly results in increasing penetration with a parallel loss in image contrast, all other parameters being equal. The cross-sectional dependence of various materials on neutron energy makes energy differences of the utmost importance in applications involving neutron radiography. Typical of this energy dependence is the cross section value for calcium as a function of neutron energy (Fig. 3). It should be noted that a random distribution for the absorption of neutrons is found primarily in the slow (thermal) energy region. For fast neutrons the cross-sectional differences tend to diminish, making the use of high energy neutrons less distinctive for forensic purposes.

In this paper the emphasis is on thermal neutron radiography with ^{252}Cf. Nonetheless, it should be noted that fast neutrons from a ^{252}Cf source prior to moderation are ideally suited for fast neutron radiography.

Imaging Neutrons

The techniques employed to image neutrons are basically different from those used to image X or gamma rays. X rays can be imaged directly with a piece of film. At present no film can image neutrons directly; hence, neutrons must be converted to a type of radiation that is easily imaged.

To convert an attenuated neutron beam into a type of radiation that is detectable, a converter material must be used. Several such materials, which emit either prompt or delayed radiation, are listed in Table 1. The first case, prompt radiation, is known as the "direct technique" and is illustrated in Fig. 4*a*. The second case, delayed radiation or residual activity, is classed as the "indirect technique" and is illustrated in Fig. 4*b*.

Feasibility Experiments

Apparatus and Experimental Technique

The type of neutron source proposed for forensic application of neutron radiography must fulfill the requirements of high thermal flux, low cost, ease of operation, small size, and portability. Californium-252 fulfills these needs. Flux values permit radiographs to be

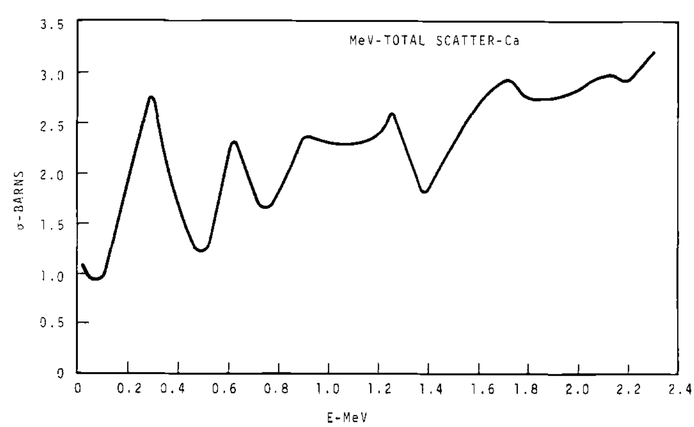

FIG. 3—*Plot of neutron cross section for Ca shows the sharp energy-dependent regions known as resonance peaks.*

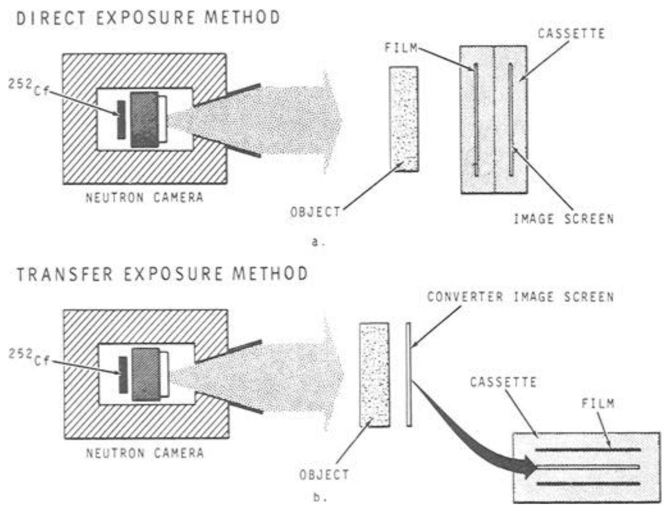

FIG. 4—*Neutron radiography—imaging techniques.*

TABLE 1—*Characteristics of several neutron converter materials.*

Material	Isotope Involved in Reaction	Relative Natural Abundance, %	Cross Section for Reaction (thermal neutrons, velocity = 2200 m/s), barns	Reaction	Half-Life
Lithium	Lithium-6	7.52	920	$^{6}Li(n,\alpha)^{3}H$	
Boron	Boron-10	18.8	3 770	$^{10}B(n,\alpha)^{7}Li$	
Rhodium	Rhodium-103	100	12	$^{103}Rh(n)^{104m}Rh$	4.5 min
			140	$^{103}Rh(n)^{104}Rh$	44 s
Silver	Silver-107	51.35	44	$^{107}Ag(n)^{108}Ag$	2.3 min
	Silver-109	48.65	2.8	$^{109}Ag(n)^{110m}Ag$	270 days
			110	$^{109}Ag(n)^{110}Ag$	24.2 s
Cadmium	Cadmium-113	12.26	20 000	$^{113}Cd(n,\gamma)^{114}Cd$	
Indium	Indium-115	95.77	155	$^{115}In(n)^{116m}In$	54.1 min
			52	$^{115}In(n)^{116}In$	13 s
Samarium	Samarium-149	13.8	40 800	$^{149}Sm(n,\gamma)^{150}Sm$	
	Samarium-152	26.8	140	$^{152}Sm(n)^{153}Sm$	47 h
Gadolinium	Gadolinium-155	14.73	61 000	$^{155}Gd(n,\gamma)^{156}Gd$	
	Gadolinium-157	15.68	240 000	$^{157}Gd(n,\gamma)^{158}Gd$	
Dysprosium	Dysprosium-164	28.1	2 000	$^{164}Dy(n)^{165m}Dy$	1.25 min
			500	$^{164}Dy(n)^{165}Dy$	140 min
Gold	Gold-197	100	96	$^{197}Au(n)^{198}Au$	2.7 days

made with short exposures. Depending on subject and technique, exposures may vary from 1 min to 2 h. Its cost at present is not considered, as low production rates would give a fictitious value. Predicted cost estimates vary from $15,000 to $20,000 for large sources in the near future.

Californium-252 is stable, with a half-life of 2.65 years, necessitating a source change only once every 4 to 5 years. One gram of ^{252}Cf produces 2×10^{12} n/s from spontaneous fission and alpha decay. An actual source change may not require the outright purchase of a new source but only the expense for the amount of ^{252}Cf burned up, as the remaining

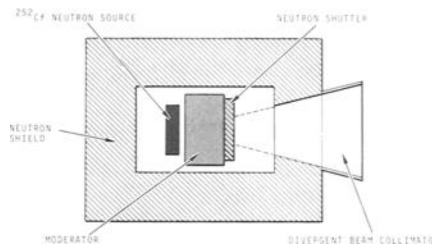

FIG. 5—*Experimental neutron radiography source camera: 10 by 10 by 12 in.; weight, ~50 lb.*

^{252}Cf in the old source may be retrievable. With ^{252}Cf there are no restrictions with regard to power hookup, etc., and the complete unit is about the same size as an X ray tube. The entire weight, including shielding, is about 100 lb.

The experimental camera used as a first-generation transportable camera for ^{252}Cf is shown in Fig. 5 and a photograph taken with it appears as Fig. 6. At present a second-generation portable neutron camera using ^{252}Cf is being fabricated. Its basic characteristics are similar to the experimental model but it is more compact, lighter, and completely portable.

Characteristics of the neutron camera used in this investigation are given in Table 2. Imaging techniques for making radiographs were both direct (Gd) and indirect (Dy) with exposure times ranging from 20 min to 2 h. All X ray film was processed in an automatic film processor to assure consistent results.

TABLE 2—*Experimental neutron camera characteristics—source: 268 μg ^{252}Cf.*

Moderator	Thermal Flux, n/cm^2·s max
CH_2 (paraffin)	7×10^5
H_2O	8×10^5
C (graphite)	6×10^5
Be	1×10^5
ZrH_2	2×10^6
TiH_2	1×10^6

Specimen Selection

As discussed earlier, thermal neutron radiography can be used to major advantage to inspect materials of low atomic weight or to differentiate between materials of nearly the same atomic number. The specimens selected for radiography are related on this basis.

General applications for neutron radiography include such areas as reactor technology, rocket and missile technology, biological studies, and basic research in physics and chemistry. These general applications are detailed in Table 3, with specific applications for forensic science given in Table 4.

TABLE 3—*General examples of neutron radiography uses.*

Object	Requirement
	General
Radiocactive heat sources	Weld evaluation
	Element continuity
	Proper material constituents
Biological studies	Tumor location
	Thin tissue studies
Plastic materials	Flaws
	Density evaluation
Physics and chemistry basics	Intermetallic diffusion processes
	Gaseous metal diffusion characteristics
	Reactor Technology
Control rods	Homogeneity
	Continuity
	Poison levels
	Inclusions and voids
Fuel elements	Homogeneity
	Continuity
	Poison levels
	Inclusions and voids
Shielding materials	Homogeneity
	Continuity
	Inclusions and voids
	Rocket and Missile Technology
Rocket fuel	Crack or fissures
Rubber tubing	Continuity
Organic gaskets	Voids
Explosive devices	Inclusions
Electron components	Material definition

TABLE 4—*Specimens selected for forensic applications.*

Specimen	Figure Number	Characteristics Useful for Solving with Thermal Neutrons
Booby-trapped ammunition	7	a. Low cross section for lead, brass, and steel
		b. High cross section for hydrogen and carbon in powder and primer
Bomb in a matchbook	8	a. High hydrocarbon content in plastic explosive
		b. High hydrogen and carbon content in paper
Gun barrel analysis	9	a. High levels of hydrogen, carbon, sulphur, etc., in powder residues
		b. High level but low cross section of lead
		c. Thick steel barrel with low cross section
Narcotics in pen	10	a. High hydrogen-carbon level in narcotics
		b. Low cross section for steel in ink filler
		c. High cross section for polymers in plastic case
Chemicals and metal in body tissue (simulated)	11	a. High cross section for H_2O in tissue (appears dense) equivalent to 2 in. flesh
		b. Chemical dispersement, relative high levels—Cl, C, H, S, Li.
		c. Metal—bismuth

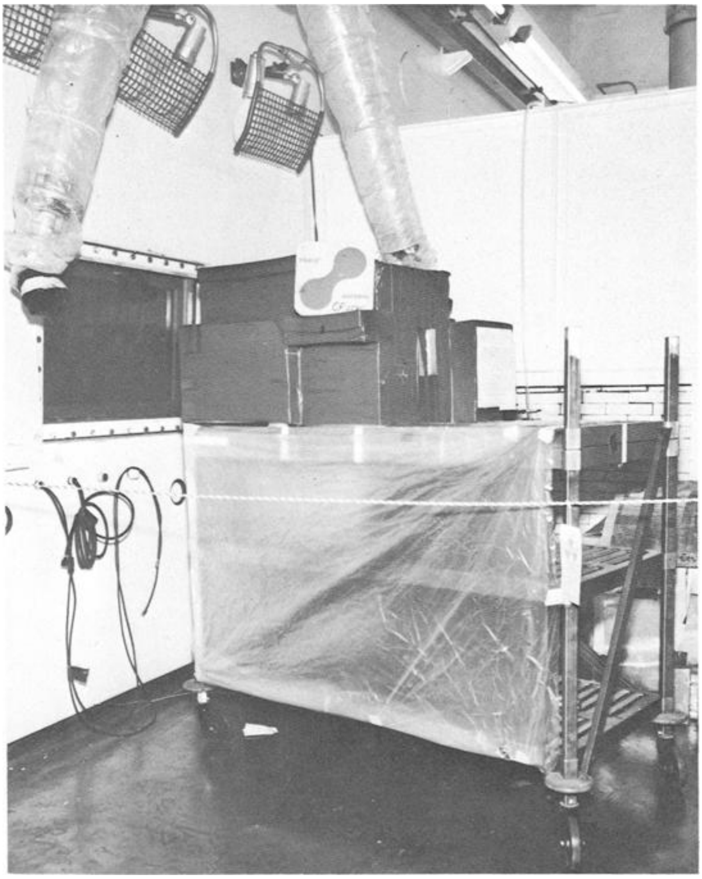

FIG. 6—*Experimental neutron camera.*

Results

Radiographic

The specimens listed in Table 4 were radiographed with ^{252}Cf and the radiographs are given in Figs. 7 through 11. A plot of the mass absorption coefficient for some materials of particular interest is given in Fig. 12. This plot provides a qualitative indication of the advantages of using neutron radiography over X ray radiography. A visual comparison of the differences between X ray and neutron radiography is given in Fig. 13.

Densitometric

In addition to providing a visual image (the radiograph), more quantitative information was obtained by scanning the radiograph and measuring the light transmitted through various portions of the image on the film. The densitometer, which measures light transmittance, is an instrument capable of providing such data.

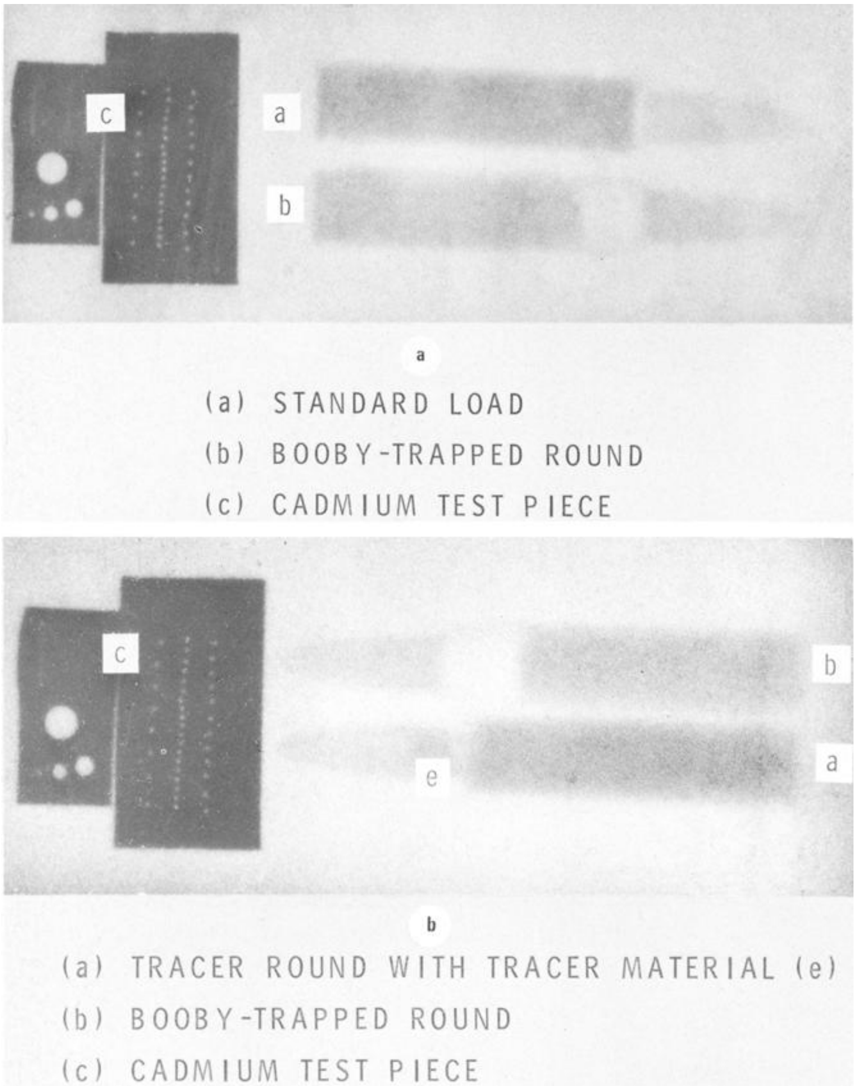

FIG. 7—*Neutron radiograph of M-16 ammunition.*

The resultant data can be plotted as relative film density (various shades of gray) versus point location on the actual specimen. Plots were obtained in this manner for the specimens in Table 5 and are given in Figs. 14*a*, 14*b*, and 15.

Conclusions

The few applications examined and presented in this paper demonstrate the usefulness of neutron radiography in forensic science. Emphasis has been placed on a portable neutron source. A complete evaluation for forensic science would require extensive

TABLE 5—*Neutron radiographs scanned with densitometer.*

Specimen	Figure Number	Summary Results
M-16		
Actual tracer round	7	1. Distinguish difference in powder material
Booby-trapped round		2. Locate primer
Standard round		3. Characterize primer material
		4. Reference powder level
		5. Distinguish slug characteristics (tracer, etc.)
		6. Locate foreign material (oil residues)
Gun barrel analysis	9	1. Relative concentration of powder residue versus actual location in barrel

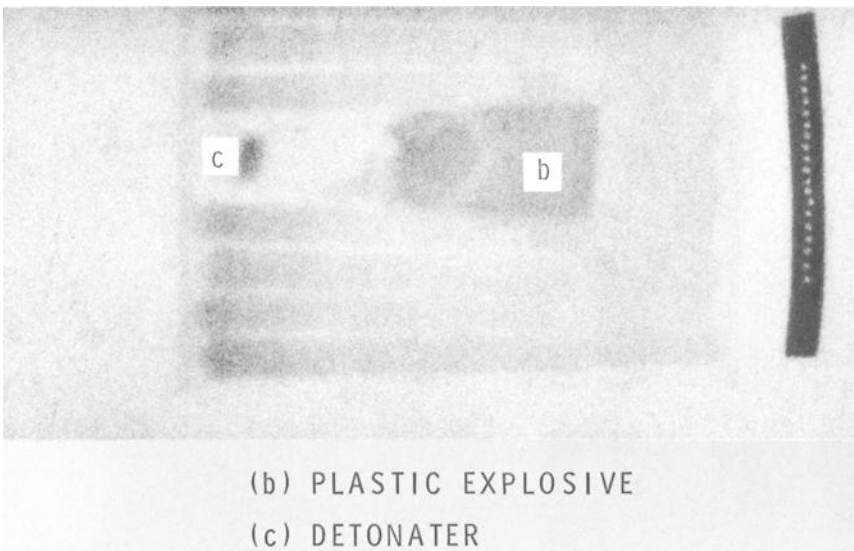

FIG. 8—*Neutron radiograph of booby-trapped matchbook.*

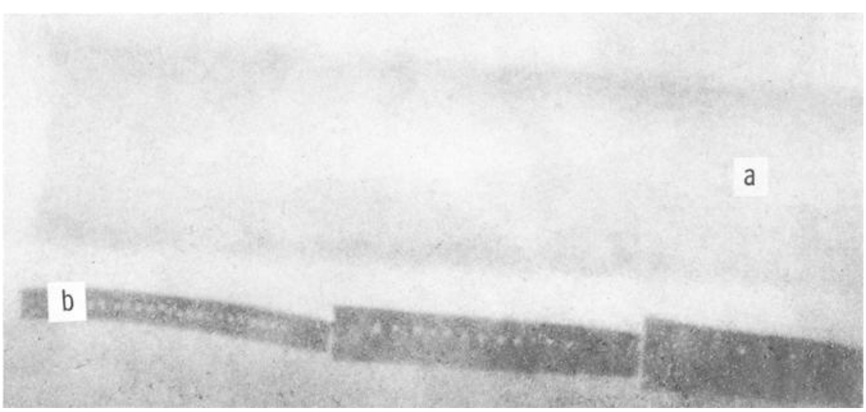

FIG. 9—*Neutron radiograph of simulated gun barrel.* (a) *Powder, lead, sulfur residues;* (b) *cadmium test specimen.*

contact between the forensic scientist and a research program such as the one presently being conducted at Battelle-Northwest. Research and development with small portable sources has been initiated and provides the technological basis for future work.

With the present availability of ^{252}Cf, the user has at his disposal one of the most useful methods developed in nondestructive testing. Association of the research scientist in

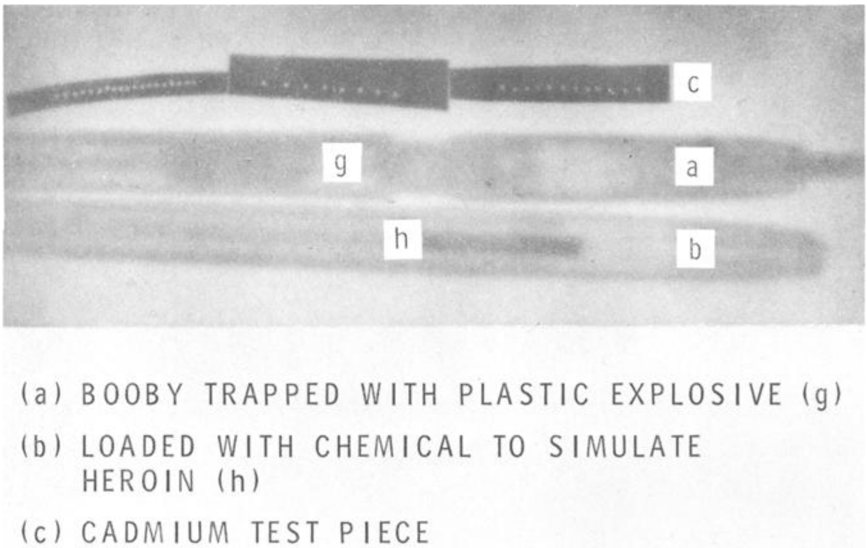

FIG. 10—*Neutron radiograph of ball-point pens.*

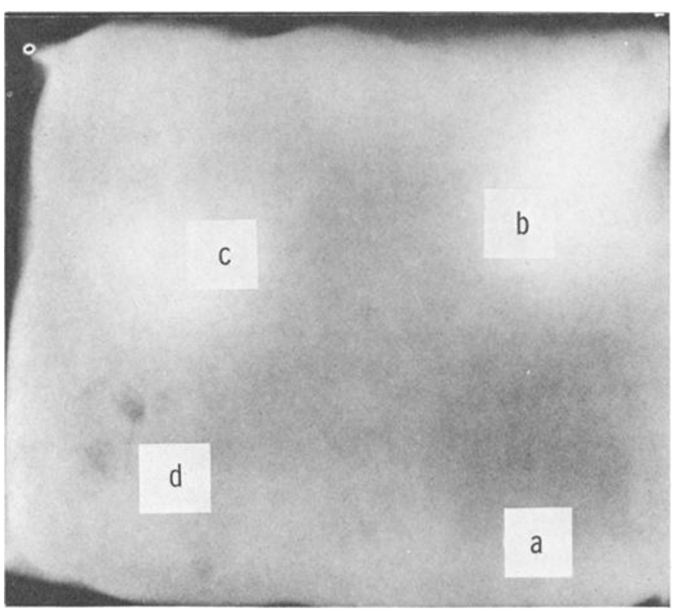

FIG. 11—*Neutron radiograph of simulated body tissue.* (a) *Specimen;* (b) *regions of high hydrogen and carbon;* (c) *chlorine and sulfur;* (d) *bismuth metal.*

nondestructive testing with people more aware of the problems in forensic science will aid in advancing the scope of applications for neutron radiography.

Further work should focus on the development of a neutron camera specifically for forensic applications. A more compact camera can be developed by identifying and tailoring only that portion of the neutron spectrum of immediate interest.

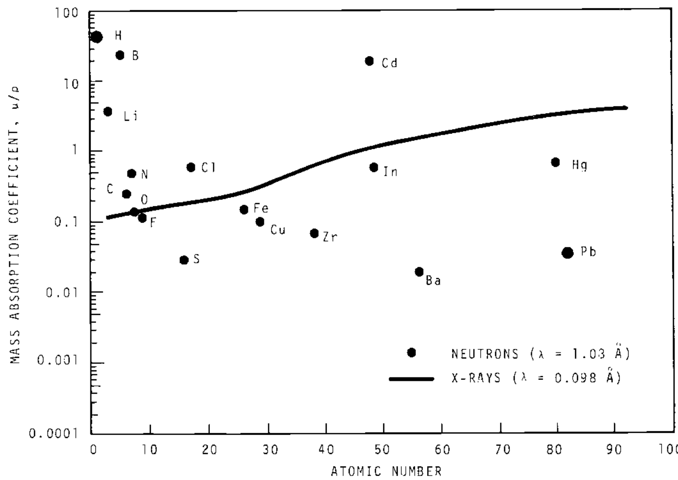

FIG. 12—*Comparison of thermal neutrons and X ray absorption for selected elements.*

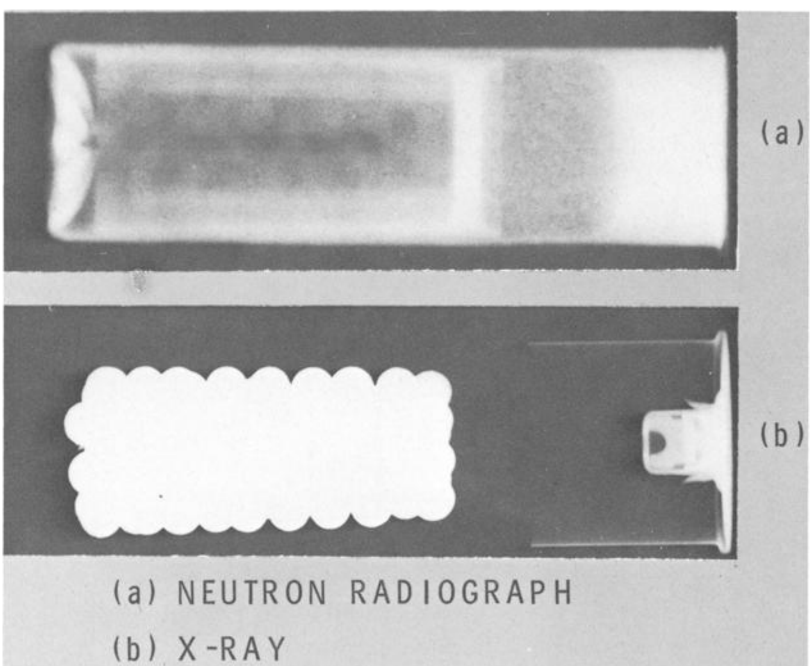

FIG. 13—*Shotgun shell.*

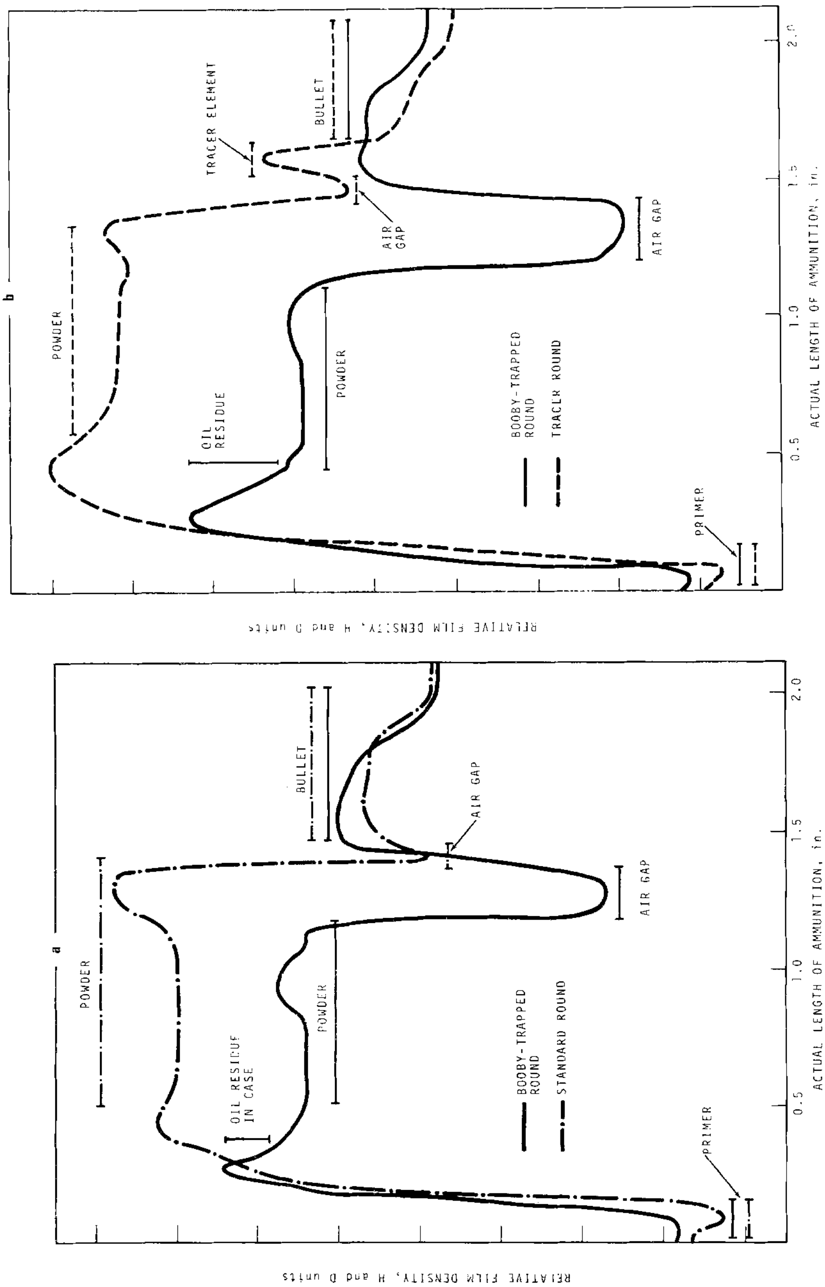

FIG. 14—*Densitometer traces of ammunition.*

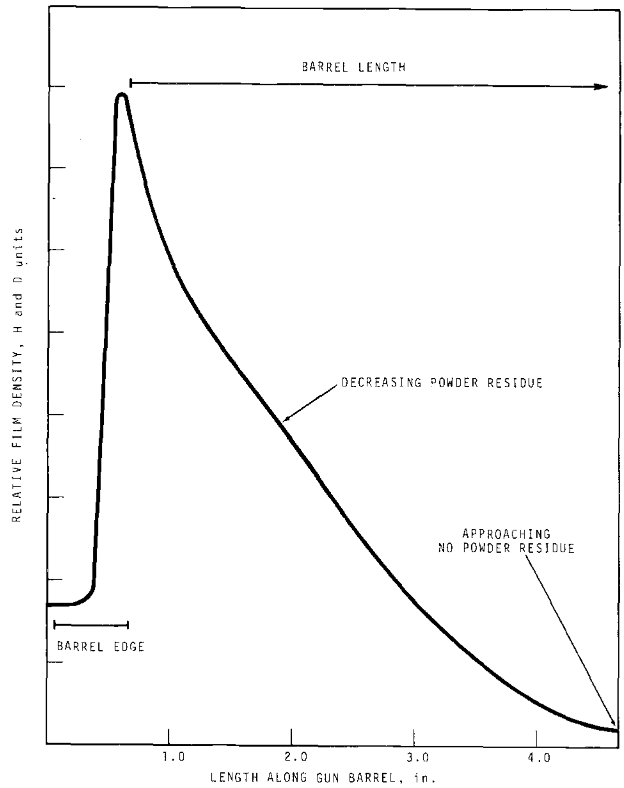

FIG. 15—*Film density scan of gun barrel with powder residues.*

Summary

Neutron radiography is fast becoming one of the most unique and useful methods in nondestructive testing. The diverse applications of neutron radiography account for the rapid development in this new field.

Neutron radiography can be a useful tool for forensic science. One can examine thick specimens (such as metal) containing hydrogen or other light element materials in either a dispersed or particle state. Examination of body tissue for regions of high specific chemical content or bones for voids or inclusions is also feasible.

Battelle-Northwest has established the potential of ^{252}Cf for neutron radiography and developed a portable neutron camera which is portable, lightweight, efficient, and easy to operate. Experimental results demonstrate the usefulness of neutron radiography as a nondestructive nuclear method in forensic science.

Possible uses include the detection of booby-trapped ammunition, bombs in a matchbook, powder residues in a gun barrel, and narcotics hidden in a ball-point pen. Other applications include problems in reactor technology such as inspection of radioactive fuel elements. In the aerospace industry neutron radiography shows promise for examining large thicknesses of cast solid rocket fuel for cracks or fissures. As a research tool in basic physics and chemistry, neutron radiography will provide a technique for diffusion studies of certain gases, boron, or other specific materials in various metals. Biological studies now underway will evaluate the possibilities of neutron radiography in this field.

As a nondestructive testing method neutron radiography will serve, in most cases, as a complementary test to X and gamma ray radiography. In other areas such as irradiated fuel studies, neutron radiography is the only acceptable method for radiographic examination.

The diverse applications of neutron radiography are the basis for exploring further applications, such as those presented by forensic science.

Gamma Industries, Inc.
P. O. Box 2543
Baton Rouge, La. 70821