Philippine Journal of Science
149 (S1): 145-150, Special Issue on Nuclear S&T
ISSN 0031 - 7683
Date Received: 18 Jun 2019

Use of Gamma Radiographic Testing to Determine the Number of Disused Californium-252 RadioactiveSources inside a Source Rod

Carl M. Nohay[1]*, **Ramoncito F. Sulit**[2], **Andrew C. Barrida**[3], **Norman Jay V. Barro**[1], **Mary Rose Q. Mundo**[1], **Joseph R. Tugo**[1], and **Cecilia M. De Vera**[1]

[1]Radiological Impact Assessment Section, Nuclear Regulatory Division
[2]Nuclear Training Center, Technology Diffusion Division
[3]Engineering Services Section, Nuclear Services Division
Department of Science and Technology – Philippine Nuclear Research Institute (DOST-PNRI), Diliman, Quezon City 1101 Philippines

DOST-PNRI licensees have three options once their radioactive sources become depleted or disused, either to a) return back the source to its principal of the country of origin, b) transfer to an authorized end-user, or c) dispose of to the Radiation Protection Services Section (RPSS) of DOST-PNRI for proper waste management. The concern began when it cannot determine the exact pieces of Californium-252 (Cf-252) piled inside a disposed source rod at RPSS due to conflicting records and lack of coordination between the user and other parties involved. The possibility of applying gamma radiographic testing has been realized as the most practical, fastest, and safest method among the other perceived techniques to determine and validate the exact quantity of Cf-252. In radiographic testing, gamma rays or X-rays are employed to check the internal structure of an item for any defects like cracks or flaws. Two radiographic shots were performed at two different angles using an Iridum-192 (Ir-192) gamma radiographic exposure device. The radiographs show the exact pieces of the Cf-252 inside the source rod disposed of at DOST-PNRI.

Keywords: Californium-252, exposure time, gamma radiographic testing, gamma radiographic exposure device, geometric unsharpness

INTRODUCTION

When a radioactive source reaches its end of life or become disused or spent, the PNRI licensees have three options to consider. The first option is to return back the radioactive source to its principal of the country of origin which is the preferred choice of DOST-PNRI in terms of safety and security issues that may arise while the radioactive source remains under the safekeeping of the licensee. Aside from this, the sending back of disused source to the country of origin will help maintain waste inventory at the Radioactive Waste Management Facility of the Radiation Protection Services Section (RPSS) of DOST-PNRI at steady pace. The second option is through transfer of ownership by selling or donating the source to other DOST-PNRI licensee for the latter's beneficial purpose. The third option is to avail of the services of the RPSS for the disposition and proper management of disused sources if the two options are not possible.

In 2016, a cement manufacturing company with a valid license to possess and store two units of Cf-252 sources

*Corresponding Author: cmnohay@pnri.dost.gov.ph

selected the third option of disposing the same at the RPSS. For some reason, several weeks after the container or "drum" was disposed of at the RPSS, it was verified that surrendered container was empty of Cf-252 sources – contrary to the claim of the company.

The date of retrieval of Cf-252 sources at the cement manufacturing facility was set and the RPSS was able to search and retrieve one source rod with an average dimension of 0.5 m in length and 0.5 cm in diameter. According to the cement manufacturing personnel, the Cf-252 sources were imbedded in series in a top-up fashion.

The challenge is to determine the actual number of Cf-252 inside the source rod acquired by the company over the years since the document submitted to the regulatory body was either insufficient or had discrepancies deemed accepted by the RPSS during the disposal of the Cf-252 sources. Unless it had been fully demonstrated and the regulatory body was satisfied regarding the exact number of Cf-252 sources retrieved and disposed of, it was presumed that one unit of Cf-252 source was missing or lost. A missing neutron source can already serve as a ground for appropriate emergency action.

In June 2018, the RPSS and the Radiological Impact Assessment Section (RIAS) within the Nuclear Regulatory Division of DOST-PNRI agreed to make an initial effort to determine the actual radiation profile of the source rod, to identify the radioisotopes inside the source rod, and to determine the possible means to disassemble the source rod to see the actual numbers of Cf-252 sources imbedded in the source rod.

The average dose rate at 1 m of 18.5 uSv/h was measured using a handheld spectroscopic personal radiation detector [Polimaster PM 1704 S/N 140332] (Figure 1).

Although the handheld isotope identifier measured the neutron dose rate at 191 cps, the said instrument failed to identify Cf-252 energy peak and instead detected other heavy nuclei isotopes.

Figure 1. The source rod containing the Cf-252 sources behind the 3" thick perspex to attenuate the free neutrons.

The gamma dose rate reading from the source rod active part using a portable multifunctional, rugged survey meter (ROTEM Model RAM R-200) was 14.4 mSv/h (Figure 2). It had been discovered that the emission of radiation was not homogenous along its angle of rotation. Turning the source rod yielded different gamma measurements.

Figure 2. The bare source rod containing the Cf-252 sources. The active part is in contact with the dose rate meter.

After examination of the nature of the source rod, the RPSS decided not to attempt to disengage the source rod but rather to get advice from foreign technical experts to make sure of the nature of the source rod, to determine what special tool is needed and the proper technique to let loose of the Cf-252, and – most importantly – to minimize radiation exposure of personnel.

Although the procedure may sound easy and simple, this was the first time at DOST-PNRI that such non-destructive testing (NDT) was performed to a radioactive source considering the risk of exposing from gamma radiation and neutrons during handling the said source rod, particularly if other methodologies were taken into consideration.

With this idea and initiative, it shows that gamma radiographic testing can be applied to radioactive sources using proper laboratory set-up, and is proven to be safe and secure for as long the planned procedures and safety measures are carefully observed. Radiographic testing is an NDT method that allows components to be examined for flaws without interfering with their usefulness. It is one of a number of inspection methods that are commonly used in industry to control the quality of manufactured products and to monitor their performance in service.

MATERIALS AND METHOD

Because there was no set period as to when the source rod will be disassembled while a missing or lost source remains a radiological concern, the RIAS devised a way to determine the content of the source rod that will provide an answer for the actual number of Cf-252 without comprising safety.

As the RIAS was pressed with time to conduct a radiological emergency survey at the cement manufacturing plant, it was thought to first seek advice from the DOST-PNRI NDT Training Team of the possible ways to examine the inside of the source rod without damaging the source rod casing.

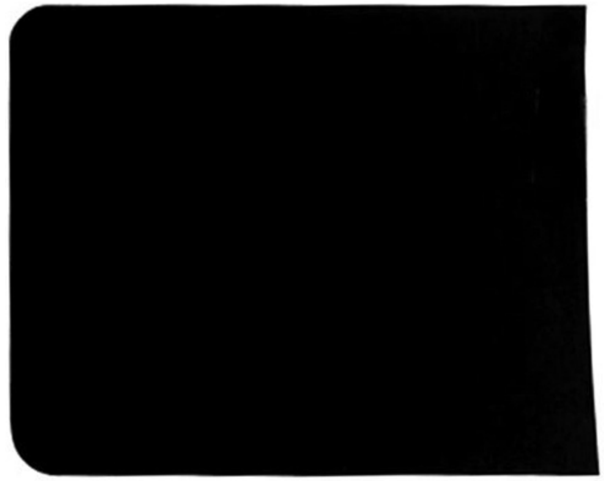

Figure 4. The overexposed radiograph as a result of the reaction of silver halide crystals all over the film.

IDENTIFYING THE BEST POSSIBLE TECHNIQUE:

According to the DOST-PNRI NDT Training Team, three possible methods can be performed. The first method was by placing the source rod directly in contact with the film. The second method was by infrared thermography. The third method was by radiographic testing.

In the first method, the source rod was laid down on the film under two different exposure time. The first exposure lasted for 2 h, resulting to underexposure. No image was formed in clear light blue acetate (Figure 3). The second involved allowing the source rod to lay down on the film for 15 h, resulting to overexposure of the film with no image seen except black (Figure 4).

The second method considered was to conduct infrared thermography whereby the source rod is heated using high-intensity light, which is then measured using an infrared camera. However, this was disregarded because the source rod is homogeneously made of stainless steel and there will be no distinction in temperature gradient from one part to another. Aside from this, the procedure may also lead to significant exposure from radiation.

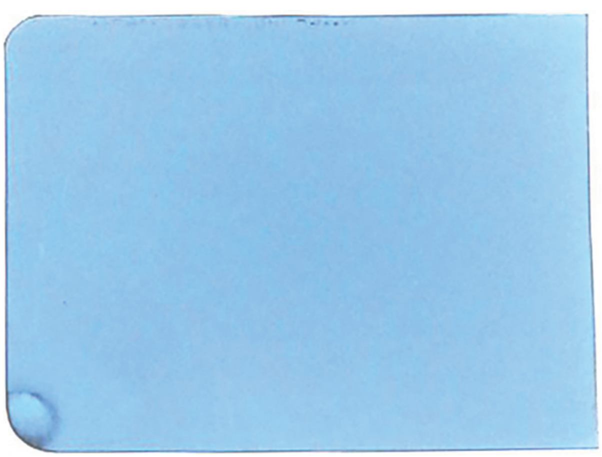

Figure 3. The underexposed radiograph in clear light blue acetate indicates less radiation interaction with silver halide crystals.

The third method was the application of gamma-ray or X-ray in a technique called radiographic testing. Radiographic testing is one of the types of NDT where a beam of gamma rays or X-rays is pointed at the subject being tested to check for product defects like cracks, inclusions, cavities, and other product-induced flaws. This method can only be carried out when all the necessary equipment are available such as the following suitable source housed in an appropriate container, guide tubes, control cable, dose rate meter, and personal monitoring devices (IAEA 1996).

According to the DOST-PNRI NDT Training Team, this was the first time that a radioactive source will undergo gamma radiographic testing. Gamma radiographic exposure device was chosen over X-ray device because the former was more readily available. This is in support of the view of Kalaga *et al.* (2009) that gamma ray source is readily available and easy to handle and use but entails serious consideration on safety.

GAMMA RADIOGRAPHIC TESTING

Prior to any activity related to the operation and handling of the gamma radiographic exposure device, the DOST-PNRI NDT Training Team had to ensure that precautionary procedures and requirements were performed as stipulated in Sections 35–38 of the Code of PNRI Regulations (CPR) Part 11 and other relevant Sections of CPR Part 3 for the optimization of protection and safety.

The radiographic procedure was undertaken using a Class P (IAEA 1999) portable gamma radiographic exposure device designed to be carried by one or more persons at the NDT Training Laboratory. Due to limited available films, two exposure shots were only performed at two different angles (0° and 90°).

The DOST-PNRI NDT Training Team calculated the exposure time (the time where Ir-192 will be on exposed position, at the tip of the guide tube), which was determined to be 60 s for each shot. Figure 5 portrays the schematic diagram of how the testing was performed.

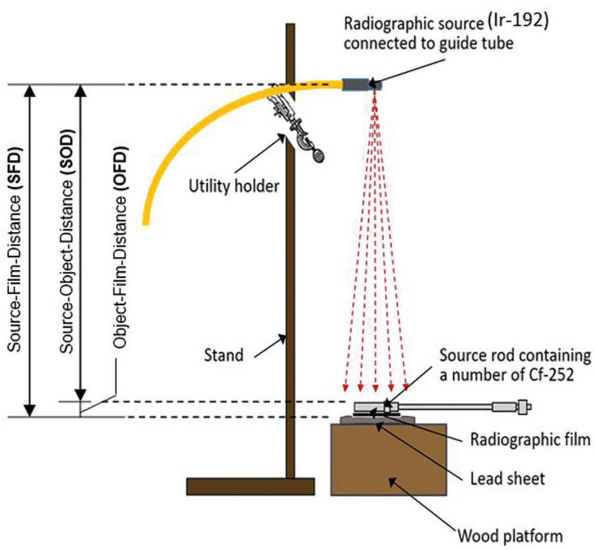

Figure 5. The industrial radiography set-up.

After the first shot, the DOST-PNRI NDT Training Team had to turn the source rod at another angle for a different impression of the rod internals. The actual set-up of the gamma radiographic testing is shown in Figure 6. Take note of the source rod's active part, which was laid bare on top of the film.

To get the exposure time or the time the film will be irradiated from Ir-192, certain parameters are needed – particularly relating to the source diameter and remaining activity (Table 1).

Table 1. Source parameters.

Source	Iridium-192 (Ir-192)
Activity	50 Ci as of 17 Jul 2018
Source model	A424-9
Source size: diameter / length / diagonal	0.106 in / 0.122 in / 0.162 in
Source rod diameter	10 mm (0.393 in)

Figure 6. The radiographic set-up showing the guide tube where the Ir-192 source is located and the source rod laid bare on top of the film.

As for the geometric unsharpness limitations, U_g, the ASME Code Section V, Article 2: Radiographic Examination, T274.2 (Table 2) was used as a reference.

For material thickness under 2 in (50 mm), U_{gmax} = 0.02 inch (0.51mm) in Table 2 was used.

Table 2. Geometric unsharpness limitations (U_g), T274.2.

Material thickness, in (mm)	U_g maximum, in (mm)
Under 2 (50)	0.02 (0.51)
2 through 3 (50–75)	0.03 (0.76)
Over 3 through 4 (75–100)	0.04 (1.02)
Greater than 4 (100)	0.07 (1.78)

$$U_g = \frac{F \times OFD}{SOD} \quad (1)$$

where:

U_g = *geometric unsharpness (in)*

F = *focal size (diagonal, in)*

OFD = object-film-distance (in.)

SOD = source-object-distance (in.)

SFD = source-film-distance (in.)

Solving for the minimum required SOD derived from Equation (1):

$$SOD = \frac{F \times OFD}{U_g} = \frac{0.162 \times 0.393}{0.02} = 3.18\ in., \qquad (2)$$

assuming SOD ≈ 20 in

Using Equation (1) and substituting assumed SOD from Equation (2), solving for the actual geometric unsharpness ($U_{g_{ACTUAL}}$):

$$U_{g_{ACTUAL}} = \frac{F \times OFD}{SOD} = \frac{0.162 \times 0.393}{0.02} = 0.003\ in.$$

Computing for the exposure time:

$$Exposure\ Time = \frac{EF \times SFD^2 \times FF}{Source\ of\ Activity} \qquad (3)$$

where:

EF = *exposure factor (Ci-min, in*$^{-2}$*)*
FF = *film factor (unitless)*
SFD = *source-film-distance (in.)*
Activity = *in curies*

Using the exposure factor table (Table 3) where thickness (t) of the material = 10 mm (0.393 in) and film optical density is 2.5, the derived exposure factor as interpolated was equal to 0.135.

Table 3. Exposure factor table.

Thickness		Density		
inch	mm	2.0	2.5	3.0
0.25	6.35	0.082	0.110	0.140
0.312	7.94	0.091	0.120	0.150
0.375	9.525	0.099	0.130	0.160
0.437	11.11	0.110	0.140	0.175
0.5	12.7	0.130	0.150	0.190

The film type used was a Fujifilm X100HD with an FF of 1.

SFD = SOD + OFD = 20 in. + 0.11 in. = 20.11 in.

Using Equation (3) and substituting the given data to compute for the exposure time:

$$Exposure\ Time = \frac{0.003 \times 20.11^2 \times 1}{50} \cong 1\ min$$

Therefore, the exposure time is equal to 1 min (60 sec) to attain an acceptable film optical density of 2.5.

RESULTS AND DISCUSSION

Figures 7 and 8 are the actual images (radiographs) of the specimen source rod. The DOST-PNRI NDT Training Team had to turn or rotate the source rod in order to establish if the source rod internals are uniform. Based on the image in Figure 7, it is evident that the three units of Cf-252 were noticeably inside the source rod and each was doubly encapsulated. It is also clear that Cf-252 sources labeled as Source 01 and 03 were identical in shape and structure, while Source 02 was completely different. This is because the main supplier of Sources 01 and 03 was the same, which was different from that of Source 02 based on the records submitted by the cement manufacturing plant to the regulatory body. It is also noteworthy to mention the different components that are discovered inside the source rod, such as the spacers/fillers, the screw thread that locks and unlocked the Cf-252 sources, and the hole or groove at the beginning and end of the active part of the source rod.

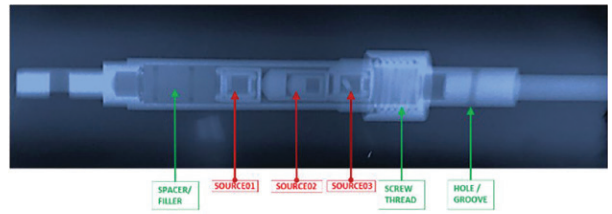

Figure 7. A radiograph taken at first shot showing the internals of the Cf-252 source rod.

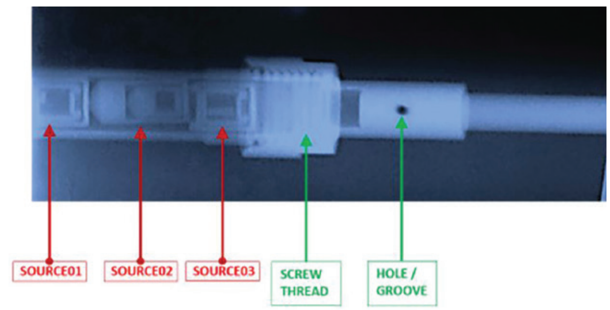

Figure 8. A radiograph at the second shot in different tangential orientation.

In Figure 8, Source 02's position had minor misalignment due to the manner of loading into the rod. More shots could have been made if sufficient number of films were available at the time of the test.

As far as exposure doses during the setup of apparatus and actual testing are concerned, the DOST-PNRI NDT Training Team only received minimal radiation doses. Electronic personal dosimeters worn by the individuals indicated a slight increase of their doses by a value of 2 uSv but did not indicate radiation exposure from neutron. The DOST-PNRI NDT Training Team completed the whole process within approximately 10 min, 5 min for bringing in and out of the source rod and 5 min for the exposure time. In addition, the thermoluminescence dosimeters have yet to be submitted to RPSS for processing.

CONCLUSION AND RECOMMENDATIONS

The results of the radiographs show vividly without uncertainty that there were indeed three units of Cf-252, all intact inside the disposed source rod. We can, therefore, say that all pieces of Cf-252 are well-accounted for. It is for the interest of establishing facts to have a readily available working gamma radiographic exposure device and ancillary items like films and chemical solutions.

This particular exercise shows how the gamma radiographic testing helped us examine the inside of an object in less time, with very minimal exposure without damaging the subject concerned. It has been demonstrated also that gamma radiographic testing can be performed for radioactive sources with low gamma energies.

Since this involves neutron-emitting radiation sources, it is high time for DOST-PNRI to consider the establishment of neutron dosimetry and, subsequently, conduct a study on the occupational workers potentially exposed to neutron regardless of its energies.

In addition, as part of the lessons learned, the RPSS should review and consider to improve its procedure on the receipt and handling of disused/spent radioactive source vis-à-vis with the existing quality procedure.

There are possibilities that the same incident will happen again in the future, unless the involved regulatory personnel will closely work together. The licensing group should be more stringent in requiring its licensee to submit hard evidences, which directly or indirectly involve the radioactive material like source replacement or source changing, importation and exportation, *etc.* On the other hand, the inspection team must be more cautious of the activities performed by the licensee. It is also recommended to strengthen continuous communication between the regulatory body and the RPSS.

It opens up the weaknesses of the regulatory activities that need to be addressed and resolved and may help bridge the gap between the two different functions of DOST-PNRI as a regulatory authority and a service provider. It also avoided performing any radiological emergency response action, as it proved unnecessary to do such response since no radioactive source was missing.

ACKNOWLEDGMENT

Our special thanks of gratitude and appreciation to the DOST-PNRI NDT Training Team for providing their technical expertise and assistance in performing the gamma radiographic testing and use of their NDT facility, and the NRD for the successful completion of this investigation.

REFERENCES

[ASME] American Society of Mechanical Engineers. 2010. ASME CODE Section V, Article 2: Radiographic Examination.

GOV.PH. 2010 Feb 08. Code of PNRI Part 11: Licenses for Industrial Radiography and Radiation Safety Requirements for Radiographic Operations. Official Gazette of the Republic of the Philippines, Vol. 106, No. 6.

GOV.PH. 2004 Sep 06. Code of PNRI Part 3: Standards for Protection Against Radiation. Official Gazette of the Republic of the Philippines, Vol. 100, No. 36.

[IAEA] International Atomic Energy Agency. 1999. Radiation Protection and Safety in Industrial Radiography [Safety Report Series No.13]. Vienna.

[IAEA] International Atomic Energy Agency. 1996. Practical Radiation Safety Manual, Manual on Gamma Radiography. Vienna.

KALAGA D, KULKARNI AV, ACHARYA R, KUMAR U, SINGH G, JOSHI JB. 2009. Some Industrial Applications of Gamma-Ray Tomography. Journal of the Taiwan Institute of Chemical Engineers 40(6): 602–612.