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THE FABRICATION OF RADIOACTIVE SOURCES

Albert E. Salo and Nelson B. Garden
(with Appendix by Herbert P. Cantelow)

October 1959

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Contents

Abstract .......................... 3
I. Introduction ..................... 4
II. Sealing ......................... 5
   A. Preparation of Uncovered Sources .......................... 5
   B. Sealing with Thin Films ................................ 10
   C. Sealing Behind Thicker Materials ....................... 13
   D. Soldering and Welding ................................. 13
   E. Leak Testing ................................. 16
III. Shielding ....................... 17
   A. Alpha Shielding ................................. 17
   B. Beta Shielding ................................. 17
   C. Gamma Shielding ............................... 19
IV. Marking .......................... 20
   A. Marking Methods ............................... 20
   B. Marking, Assays ............................... 21
Appendix: Source Control and Evaluation ..................... 22
Bibliography ........................ 27
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Lawrence Radiation Laboratory
University of California
Berkeley, California

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ABSTRACT

Techniques and arts used in preparing alpha, beta, and gamma radiation sources at Lawrence Radiation Laboratory are described. Methods for securing relatively swipe-free open sources as well as methods for sealing closed sources are outlined. Suggestions are given also for leak testing, shielding, and marking. The problem of source preparation is approached from a practical viewpoint, and theoretical aspects are touched only lightly.
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I. INTRODUCTION

At Lawrence Radiation Laboratory radioactive sources have become increasingly important in research and in electronic maintenance. Originally, individual users attempted to prepare their own sources, but they were often inexperienced in handling radioactivity; ever-widening use of sources frequently gave rise to expensive or potentially dangerous situations. A specially trained group in Health Chemistry, using special equipment and techniques, has now been assigned to prepare, calibrate, issue, inventory and periodically inspect radioactive sources, in accordance with the Lawrence Radiation Laboratory policy of keeping radioactivity under control at all times.

Since late 1951, when this service was started, nearly 1000 sources have been fabricated and issued. In strength these sources have ranged from μC of nickel-65 to 2000 curies of cobalt-60 delivering about 10,000,000 roentgens per hour at 1 cm. In size they have ranged from a 5-mil silver wire 1/4 in. long to a lead and steel structure weighing nearly 5 tons. At Lawrence Radiation Laboratory there are two general classes of sources to be considered: (a) physical sources such as Van de Graaff machines, cyclotrons, and linear accelerators, and (b) chemical sources in which the origin of ionizing radiation is the atomic disintegration of any radio-

Physical sources are capable of directly supplying high-flux beams of electrons (β−), positrons (β+), protons (1H+), deuterons (1H2), alpha particles (2He4), and heavy ions up to neon, as well as indirectly supplying many types of radiation including neutrons (0n1), gamma and x-rays (electromagnetic waves of 0.001 to 100 angstroms in length), mesons, hyperons, antiprotons, and strange particles.

Chemical sources may be (a) made on a physical source machine under bombardment by any one type of the accelerated particles mentioned above, (b) made as a result of neutron capture and spallation in a reactor which itself is a chemical source, (c) occur in nature. They emit, as far as is known, only alpha particles, positive and negative beta particles, gamma and x-rays, and neutrons.
Health Chemistry, by assignment, is concerned only with chemical sources. The term "source" herein refers to chemical sources. For many research purposes a chemical source has advantages over a physical source machine in that (a) it is usually small and capable of being transported, therefore it lends itself better to bench-top experiments, and (b) within the limits of its half life it supplies a constant field of energy independent of electric and mechanical power. On the other hand, its disadvantage is that, unless it is a neutron source of the fission or α, n type, it cannot be shut off. It goes on radiating throughout its natural life, and is a potential hazard to anyone who might come in contact with it.

To minimize its potential hazard a good source should be (a) sealed off from the external environment to prevent the escape of even small masses of the source nuclide, (b) adequately shielded to prevent exposure by its ionizing radiation, and (c) plainly marked with a radiation symbol and with notations of its chemical identity, its disintegration rate, and its radiation level both shielded and unshielded. A proposed logical basis for determining the potential hazard is outlined in the Appendix.

II. SEALING

The proper sealing of a source is to be considered of primary importance for two reasons: (a) it offers protection against the hazard of ingestion by the human body, and (b) a leaking source can contaminate equipment and introduce unwanted effects into an experiment. Several source-sealing techniques have been developed. Which methods and materials are used depends upon such factors as the type of radiation, the disintegration rate, the space and mass limitations imposed by the intended use, the energy requirements of the experiment, and the length of time the source will be in service.

A. Preparation of Uncovered Sources

The simplest source is one that consists of a metal, plastic, or glass disc upon which a given amount of radioactive material is pipetted and dried. If the activity level is low enough and the specific activity is high enough so that only a very small mass is necessary, the source material may adhere to the surface of the disc strongly enough that it will not rub off on a rubber glove with moderate hand pressure. Such a source is considered "swipe negative" and for all practical purposes is a sealed source. Experience has shown that the upper level of activity permissible for this type of source is about 0.1 μC/in.², where the specific activity is not less than 0.1 μC/μg.

Stock solutions from which these simple disc sources are deposited usually range from 0.1 to 1 N nitric or hydrochloric acid. The material of which the disc is made therefore should be able to withstand chemical assault accordingly. The disc material should also be capable of withstanding any corrosive conditions that might be encountered in the environment in which the source is to be used or stored. It has been found, for example,
that aluminum and stainless steel often produce scale which subsequently flakes off, carrying the radionuclide with it. Platinum, therefore, is to be preferred in most cases.

Frequently, however, platinum is ruled out by the conditions of intended use. For example, where beta standards are required, backscattering—which increases with increasing electron density or atomic number—is to be kept to a minimum. Aluminum with its low atomic number, is often specified here; in this case it is advisable to neutralize the stock solution before the radionuclide is deposited. Carbon, glass, or lucite may also be used. Glass or lucite imposes limitations on how much heat can be applied in drying. The bonding strength between nuclide and disc can be increased by flaming or baking in an induction coil, but lucite and glass cannot be heat treated and cannot be expected to hold so much active material as metals or carbon.

Although a simple disc source may be swipe-negative when it leaves the source-fabrication laboratory, it may not remain so indefinitely. Bombardment from its own radioactivity tends to loosen the bonding. Periodic inspections based on the hazard-evaluation system outlined in the Appendix must be made. If the source is found to be losing material, it must be returned for repair, recalibration, or replacement.

To increase the bonding between nuclide and disc, special techniques other than deposition and drying from solution have been devised. The next most simple method is electrodeposition. Electrodeposition can in some cases be accomplished without external current. Concentrations of Po\textsuperscript{210} up to about 1 \( \mu \text{C/cm}^2 \) can be readily obtained on silver discs in 0.1 N nitric acid solution by the chemical replacement reaction

\[
\text{Po}^{+++} + 3 \text{Ag} \rightarrow \text{Po} + 3 \text{Ag}^+.
\]

When higher concentrations of polonium are needed, it is more time-saving to apply to the system a direct current at about 0.8 v, using the disc as the cathode and using a carbon anode.\textsuperscript{2} About 10% of the deposited polonium will be found on the anode, however—probably because of complexion formation. When external current is used the disc material is not restricted to silver or other metals that can be replaced by polonium. Any metal that is a good electrical conductor and does not react with the electrolyte may be used. Acid concentrations between 0.01 and 0.1 N are used in the electrolyte.

Electrodeposition, with or without current, is of course restricted to metals such as nickel, cobalt, gold, and polonium. Elements such as sodium, cesium, and strontium— isotopes of which provide popular and useful radiation spectra—are ruled out. Researchers have reported success


in electroplating uranium and other actinides, but duplication of their results is difficult to achieve. What appear to be tight deposits on the disc while it is immersed in solution or is in an inert gas usually flake off immediately on contact with the oxygen of the atmosphere.

Alternates to electrodeposition for securing more tightly bound deposits on discs are flashing or sputtering.

**Flashing**

Flashing involves evaporating the source nuclide in a vacuum and condensing it on a cold surface. The device used for this purpose consists of a bell jar which can be seated with an O-ring gasket on a flat metal plate, a Kinney mechanical vacuum pump, an oil diffusion pump, a resistance heating circuit backed by an 8-kw ac power supply, a 1.5-kv dc power supply, and suitable gages for measuring vacuum and power. The entire assembly is then enclosed in a glove box of special design (Fig. 1). A minimum vacuum of $5 \times 10^{-5}$ mm Hg is necessary, but $10^{-6}$ mm Hg is better.

Small amounts of material may be evaporated directly from the filament, but usually the nuclide to be flashed is deposited in a small carbon crucible. The crucible is connected to the positive lead of the high-voltage circuit. The negative lead of the high-voltage circuit is grounded to the bell-jar platform which, of course, must be well insulated from the crucible. Around the crucible, close but not touching, is wound a resistance wire of 20-mil tungsten which is connected to the ac power supply. This filament is also grounded to the platform. The catching disc is mounted above the crucible opening at distances up to about 0.5 in. (Fig. 2). If the disc will not remain cool enough during operation, to condense the nuclide material, it may be mounted in a cooling block in which water is circulated over the back of the disc.

After the desired vacuum has been attained, the crucible is heated. First the tungsten resistance filament is heated to about $1000^\circ$ C by feeding in gradually increasing current through a variable transformer. Then high-voltage dc is applied slowly to the crucible, which is bombarded by electrons emanating from the wire filament and dropping through the potential of 1 to 1.5 kv. The crucible in most cases attains temperatures sufficient to evaporate most materials. Care must be taken not to increase the temperature so much that excess carbon itself sublimes and condenses on the plate.

Sources made by the flashing method are characterized by uniformity and thinness of the deposit. The maximum permissible amount of swipe-negative deposit may be from 10 to 100 times that from solution. Disadvantages of the flashing method are that usually only 10% recovery is obtained. Also, the flashing method requires great care in placing the crucible so that it does not touch the filament, and such dexterity is not possible with remote tongs or manipulators. Application by flashing is

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Fig. 1. Vacuum evaporator and enclosure.
Fig. 2. Operating platform for vacuum evaporator.
therefore largely limited to alpha emitters, which can be easily shielded.

Finally a major disadvantage in flashing is that in many cases evaporation takes place below the boiling point of the material being flashed. As a consequence the rate of transfer is low. Low rates of transfer are not serious for high-specific-activity nuclides, but with materials such as \(^{238}\text{U}\), of which greater masses must be transferred at a higher rate, sputtering is preferred to flashing.

**Sputtering**

Sputtering differs from flashing in that the electrodes are switched. The material to be transferred becomes the cathode instead of the anode. Bombardment is by positive ions rather than by electrons. Particles are dislodged by displacement at ambient temperature; the heating filament is eliminated. The operation takes place in that range of pressure in which we find corona discharge. An argon atmosphere of about \(2.5 \times 10^{-2}\) mm Hg is used instead of a vacuum of \(10^{-5}\) mm.

**Shapes**

Although the disc shape is the most popular of the simple, uncovered sources, such shapes as wires, dishes, foils, screw heads, or tubes are frequently needed. Nuclide-depositing techniques, with minor variations, are similar. In some cases dipping and drying may be used instead of pipetting.

**B. Sealing with Thin Films**

If higher levels of activity are needed than are considered safe for an open disc, the nuclide deposit may be covered. The simplest form of covering is an organic film. An organic film may be applied as a lacquer and dried. The nuclide may be mixed with the lacquer before application, but more often the lacquer is applied over the dried deposit. Satisfactory lacquers for this purpose are a material called Zapon, thinned 6 to 1 with special Zapon thinner and applied with a dropper, or a material called Krylon, which is sprayed from a spray can.

An organic film may also be applied as a solid. For this purpose 1/4-mil Du Pont Mylar is used. A solid film must be secured to the disc, usually by gluing with Duco or Hysol cements. Cementing must be done either on the back of the disc or on a portion of the face that is not covered with the radionuclide.

Limitations on organic films are imposed by the level and energy of the radioactivity: \(10^8\) rep is considered the upper level of total radiation to

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which these organic films may be exposed without serious damage. One mC of an equilibrium mixture of strontium-90 and yttrium-90, a popular beta source, with a maximum beta energy of 2.5 Mev, delivers a dose rate to a contacting film of about 10,000 rep/hr. Since there are about 10,000 hours in a year, an organic film over a 1-mC Sr$^{90}$-Y$^{90}$ source could be expected to last no longer than that.

However, strontium-90, a bone-seeker, is especially hazardous if ingested, therefore, a safety factor of 10 is added. Except under unusual conditions of strict control no strontium-90 source over 0.1 mC would be issued if sealing were dependent on a thin organic film. An inorganic film, such as 1/4-mil aluminum or thin mica, may be used instead of an organic film. Inorganic films, however, either require an organic glue or an organic gasket, so that the dose level to the glue or gasket still must be considered.

Any film, organic or inorganic, interferes with the energy spectrum of a beta or alpha emitter (Fig. 3 and 4). Usually in high-energy beta emitters energy interference from a thin film is not considered important. For instance, an absorber of 7 mg/cm$^2$ thickness passes 95% of the beta activity, maximum energy 1.7 Mev, from phosphorus-32. In weak betas however, and all alphas, even a thin film may be serious. For example, Mylar 1/4 mil thick lowers and broadens and makes fuzzy a 5-Mev alpha energy peak. Sources whose requirements are energy-dependent, therefore, cannot be covered with anything. Fortunately most requests for alpha sources do not specify energy dependence, and 1/4-mil Mylar can be used to good advantage.

A very thin metallic film placed over a source by the flashing technique described previously, is independent of the weakness of organic cements or gaskets. After the nuclide has been deposited, the crucible may be charged with gold or aluminum and flashed in the same manner as the nuclide. Thickness of film may be calculated by weight.

C. Sealing Behind Thicker Materials

Gamma sources and high-energy beta sources in the range of 10 to 500 μC may be sealed in plastic containers of various designs. The simplest design of this type is a polyethylene pillbox 3/4 in. high, from 1/2 to 1-1/2 in. in diameter, with 1/16-in. walls. The source disc is cemented to the bottom of the pillbox with Hysol and the cover is sealed on with the same material. Another design is a rectangular lucite block with a milled indentation slightly larger in diameter than the source disc (Fig. 5). A second lucite block or sheet, which may be of any thickness, is placed over the base block and cemented with lucite cement.

A third design of this type, which has been employed strictly for beta sources, is a cylindrical lucite assembly 3 in. in diameter by 4 in. high (Fig. 6). The source disc is mounted in an indentation at the center of one end of the main body. Over the source is placed a thin mica circular sheet.

Fig. 3. Degradation of alpha particles by 0.00025-in. Mylar (Almon E. Larsh, by personal communication, 1/3/58).
Fig. 4. Effect of Lucite absorbers on the energy spectra of P$^{32}$ beta rays.  
A: no absorber; B: 24 mg/cm$^2$; C: 90 mg/cm$^2$; D: 237 mg/cm$^2$. 
Fig. 5. Portable beta source holder.
Fig. 6. Portable beta source holder.
held in place by Duco cement and a metal retaining ring. A removable relief-threaded shielding cap completes the assembly.

D. Soldering and Welding

All sources sealed in plastic are of course subject to the radiation dosage limitations mentioned before. All-metal or all-glass containers are preferred to plastic when high levels of activity are involved. Sealing of metals is by soldering or welding of glass, by fusion.

A general rule to follow in soldering or welding source seals is to keep the soldered or welded joint as small as possible. The easiest shape to seal is a small-diameter tube, one end of which has been sealed before the radioactive material is loaded. It is important to choose a material that is easily soldered, such as brass or copper. Pretinning the solder contact and taking the usual precautions for keeping the tinned surface clean are also important. It is best, therefore, to load the tube with solids rather than solutions. The most commonly used solid source nuclide material would be a powder obtained from drying a solution. To insure uniform distribution in the tube these residue powders may be mixed with an inert material such as powdered carbon. The inert material must be one that will not give off gases under decomposition caused by the radioactive bombardment. Powders are introduced into the tube through a small funnel, the stem of which is inserted to a depth below that of the tinned surface.

For cobalt-60, irradiated pellets of cobalt metal are used in loading the tubes. In this metal there is an added advantage—the pellets can be picked up and released with an electromagnet to facilitate handling.

Having the radioactive material deposited on a wire or rolled in a thin metal foil also makes for easier tube loading and a clean tinned surface at the end to be soldered.

In soldering, organic fluxes are to be avoided if possible. The solder is cleaned with hydrochloric acid and washed with water followed by acetone. If the solder is cut with a flare it will rest on the lip of the tube without dropping in and touching the active material. The pieces are cut so that they protrude about 1/4 in. from the end of the tube (Fig. 7).

Heat is applied to the solder through a carbon electrode about two in. long by 3/8 in. in diameter, tapered to a fairly fine point. The carbon electrode is connected to either post of a 6-v lead-acid storage battery. The other battery connection runs through an alligator clip to the metal tube. Since sources requiring this type of seal are usually high-level beta or gamma emitters, the loading and soldering must be done at a distance behind lead shielding. The battery leads, therefore, must be flexible for easy manipulation yet heavy enough to carry about 100 amperes. When the carbon tip is touched to the solder, the solder melts and runs down into the tube opening. The electrode is held until a good melt is obtained.
Fig. 7. Source tube before final sealing.
In some cases, such as medical applicators, copper cannot be used, but gold or platinum may be specified. In these cases welding is necessary. The same technique is used for welding except that a gold or platinum plug is used instead of solder, or--if permissible--the end of the tube may be crimped after loading and be welded without the addition of more metal. The carbon electrode and battery used for soldering have been found adequate to melt platinum under these conditions.

Shapes other than tubes may be required for soldering. Points to be remembered here, in addition to those already mentioned, are: (a) a reservoir for the solder must be provided at the joint to be sealed, (b) the solder must be heated locally, a small section at a time.

Glass tubes may be sealed by standard glass-blowing techniques except that the operation must be done in an enclosure fitted with gloves or remote handling equipment. Special precautions, such as lining the enclosures with asbestos, must be taken when open flames are used. The torch is usually lighted by means of a Tesla coil to preclude the necessity of striking matches.

A disc source composed of two thin platinum plates with a gamma emitter sandwiched between them may be sealed with the aid of silver solder and an induction heater. A narrow strip around the entire circumference on one face of the disc is first treated with an inorganic flux. A silver-solder wire is then formed in the shape of a circle to correspond to the diameter of the flux. Disc and wire are placed in the center of an induction coil powered by a 300-watt high-frequency generator. Current is applied slowly until the silver solder melts. After the solder has cooled the second disc is added. Again the assembly is heated to the melting point of silver solder. A mild pressure may be applied during the second heating by holding a ceramic tube of equal diameter against the rim.

Other source fabricators at other sites have developed heliarc welding techniques for sealing sources. We have not adopted these techniques here.

All sources are fabricated in glove or manipulator enclosures, and the exterior of a source is often contaminated after it has been loaded and sealed in a contaminated enclosure. A preliminary decontamination is carried out in the loading and sealing enclosure and the source is then removed to an enclosure of lower environmental activity level to complete the decontamination. The source is then ready for testing of the seal.

E. Leak Testing

Leak testing usually consists of a liquid-immersion test followed by a gas-transfer test. The source is immersed in water for as long as the intended user will allow. The water is then evaporated and the residue is assayed for radioactivity. If the assay is positive the test is repeated. Residual contamination on the outside of the source shows up in the assays as a decreasing radioactive count. Leakage from the inside shows up as a steady or increasing count.

A. Richmond (Mound Laboratory) and J. L. Shepherd (Isotopes Specialties Co.), personal communications.
If the source passes the immersion test it may be tested further by a helium-transfer method. In this test the time required to sweep helium from a chamber containing the source is compared with the time required to sweep the same amount of helium from the same chamber containing a dummy that is of the same volume as the source. The chamber containing the source is evacuated, then filled with helium. If there are any small holes in the seal of the source, helium enters the source cavity. The chamber is then swept with argon. Any helium in the source cavity diffuses slowly back through the holes, lengthening the sweep time. Helium remaining in the chamber after the argon sweep can be detected by pulling the gas into a spectrographic leak detector such as the Consolidated Engineering Co. Model 24-101 A.
III. SHIELDING

After a source has been successfully sealed, it must be adequately shielded. The ultimate goal in shielding is no detectable radiation outside the shield. If complete shielding is not possible, the level should be as low as practicable.

A. Alpha Shielding

Alpha particles are usually of higher energy than beta particles or gamma photons, but because of their comparative size and their corpuscular nature they are the easiest to shield. A shielding substance of 7 mg/cm² is sufficient to stop completely the most energetic alpha particles ordinarily encountered from chemical sources. An alpha source, therefore, is customarily packaged in a cardboard folder with a hinged cover. If the intended use permits, the disc upon which the nuclide is deposited is cemented to the cardboard for added protection against damage or loss of material by dropping or mishandling. Cardboard, however, being organic in nature, is dose-sensitive. For example, a 30-mC polonium-210 source burned through 1/16-in. cardboard as neatly as the lighted end of a cigarette. Organic materials cannot be used for shielding except for sources having low disintegration rates.

Some alpha decays are accompanied by gamma rays (e.g., in Am²⁴¹), which may require additional shielding, as outlined in Section IIIC. Alpha particles in contact with materials of low atomic number, particularly beryllium, may lead to the production of neutrons and thus require paraffin or other hydrogeneous shielding.

B. Beta Shielding

Beta radiation can be partially or completely shielded by given thicknesses of any material. The choice of material depends on the energy-distribution spectrum. Light-weight materials are to be preferred because they give rise to less secondary radiation or bremsstrahlung, which are low-energy gamma or x-rays. A typical beta-shielding problem is the one presented by the source design known as the beta gun (Fig. 8). Here a highly collimated beta beam is desired, of sufficient intensity to calibrate counters or trip certain electronic mechanism. Because of the collimation, only a small fraction of the total beta rays was available at the muzzle, and it was necessary to use a large amount of Sr⁹⁰-Y⁹⁰ (3 to 5mC). The active material was deposited in a carbon cup and dried on a hot plate. The cup was in turn mounted at the head end of an aluminum screw mechanism fitted with a collar cap to hold the cup in place. The aluminum screw assembly was then screwed into a brass outer housing.

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7 Kinsman, op. cit., p. 154.
8 S. J. Wygard, Nucleonics 13 (7), 44 (July 1955).
Fig. 8. Beta-ray gun.
The carbon and aluminum, used near the source material, both being light materials, did not give rise to much secondary radiation. The brass housing served to shield what gamma secondary radiation was formed. This combination of materials cut the external radiation level by a factor of 10 below that obtained from a previous design in which a brass screw assembly holding the strontium was mounted in a lead shield.

Shielding of the collimated beta beam was accomplished by a 1/4-in.-thick brass disc which in turn was connected to a spring-loaded trigger mechanism which could be operated with a press of the thumb, or could also (with slight variation in design) be connected to a solenoid and operated electrically.

The source material was sealed in the beta gun by means of a 1/4-mil aluminum diaphragm mounted between the source and the triggered shield and held in place by an aluminum retaining ring. In early designs the strontium was deposited in the cup in the form of chloride, but this resulted in corrosion of the sealing diaphragm---probably by release of atomic or ionized chlorine---to the point of disintegration, thereby causing a serious contamination incident. Changing the chloride to carbonate before deposition seems to have corrected this defect.

Plastics, such as lucite, are often used for beta shielding. Hinged lucite boxes are quite popular as well as the screw-capped cylindrical block described earlier. Again the limitation due to the possible deterioration of organic materials under radioactive bombardment must be considered.

Beta-plus (positron) emitters, such as fluorine-18 or sodium-22, are more difficult to shield than β⁻ (electron) emitters. Positrons colliding with electrons produce annihilation gamma rays at 0.5 Mev, which is a considerably higher energy than bremsstrahling. Shielding of positrons therefore requires both beta and gamma shielding.

Gamma shielding in addition to beta shielding may also be required where beta decay is accompanied by gamma transitions (e.g., cesium-137).

C. Gamma Shielding

The general problem of gamma shielding is dealt with in either or both of two ways: (a) distance, in which the inverse-square law applies, or (b) materials in which high electron density is the governing factor. As a first approximation in estimating the shielding requirements of a given source the formula used is

$$\text{roentgens per hour at one foot} = 6CE,$$

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9Kinsman, op. cit., p. 56.
where $C$ is the curies strength of the source and $E$ is the energy of the photons. The half-thicknesses (or relaxation thicknesses) of most materials are well known\textsuperscript{10} and can be incorporated into the basic formula to obtain any desired shielding.

Two points often overlooked in practical application of shielding laws are (a) shine and (b) voids in the shielding material.

The problem of shine usually causes difficulties in shields that consist of two or more components. The 2000-curie Co\textsuperscript{60} source, for example, was designed so that there was at least 10 in. of lead between the cobalt charge and personnel in the vicinity.

In order to introduce samples of material into the irradiation chamber, however, it was necessary to have sliding shields below and above the central component. The interfaces between the fixed central component and the sliding surface, although permitting no direct radiation, allowed passage of enough shine radiation to constitute a considerable hazard. The installation of a properly placed lead ring corrected the condition.

Shielding material is usually tested for voids by x-ray film fixed to the outside of the shield. Areas that are less shielded, of course, show up darker on the film. Very often complete melts of large lead shields have to be poured again because of voids.

IV. MARKING

Since sources may come in almost any shape, and ionizing radiation cannot be detected by human sense organs without the aid of ionization devices, proper marking and identification cannot be overemphasized. Generous use of the radiation symbol on tags and labels is highly recommended.

A. Marking Methods

Where possible, as in disc sources, an identification number is stamped with a metal die directly on the basic source component. A corresponding number is recorded in a bound log book along with a notation of the nuclide, the chemical and physical form of the source, its disintegration rate or curie strength, and packaging. In addition, a label bearing the radiation symbol and other pertinent information on the source is placed on the primary shield, such as the cardboard folder or plastic box. In addition, a secondary package is also provided--usually a cylindrical ice cream carton, again labeled with symbol and pertinent information.

Source forms such as wires, screws, and small tubes of course cannot be stamped. It is advisable in these cases to package the source in a plastic or metal container that can be stamped.

\textsuperscript{10}Ibid., p. 141-152.
Although printed labels are to be used copiously, printing often wears off during handling. Die-stamped letters or numbers as near the basic component as possible at least help assure that the source will not lose its identity. If a source is an integral component of a piece of apparatus, the outside of the apparatus can often be stamped. Small capsules can sometimes be attached to a wire or chain which can be fitted with a stamped metal tag at the other end.

In addition to labeling and marking, special instructions are given to the source user. It is very important that the original specially instructed user be made personally responsible for the source, thereby discouraging the practice of lending and retending until the source ultimately falls into the hands of persons not fully aware of its hazards.

B. Marking, Assays

Assays to determine the disintegration rate or curie strength to be marked on the label of the source package can be done by any of a number of standard methods.

Alpha counting up to about \(10^5\) dpm or 0.05 \(\mu\)C is done with either a zinc sulfide scintillator or an argon proportional chamber, both of which count at 50% geometry. Where assays must be made accurately at higher activity levels a zinc sulfide scintillator is equipped with a collimator and a long metal tube which can be evacuated to reduce the counting geometry. Where estimations suffice, a survey meter equipped with a Mylar-covered ionization chamber may be used.

Beta counting at levels up to about \(10^7\) betas per minute or 5 \(\mu\)C is done with end-window Geiger tubes if the energy is such that a considerable portion passes the 3-mg/cm\(^2\) window. Lower-energy betas, such as those from Cl\(^{14}\), must be counted in an internal flow chamber. Higher disintegration rates may be determined by (a) attaching a lead collimator to the Geiger tube, or (b) assaying aliquots of the nuclide solution before deposition.

Gamma determinations are made by counting with a sodium iodide scintillator hooked up to a scaler device equipped with a variable pulse discriminator to permit assay at discrete energy levels.

In addition to the disintegration rate, the dose levels, both shielded and unshielded, should be marked on the source label. Dose levels are determined by portable Geiger-type counting-rate meters, by portable ion chambers called Junos, by photographic films, or—for very high levels—by calorimetry.

This work was done under the auspices of the U.S. Atomic Energy Commission.
APPENDIX: SOURCE CONTROL AND EVALUATION

There is need for a systematic method for impressing on each source user how great a hazard is associated with the source; we also need control measures to ensure the safe use of all sources. By extending the methods of K. Z. Morgan et al. for computing short-term exposures, we can evaluate the hazard associated with a given radioactive source.

We make use of a unit called the "potential hazard unit" or "PHU." This unit is essentially the number of microcuries of a nuclide that, taken into his body during a brief period of exposure, might be expected to give an individual his total maximum permissible dose of radiation.

This quantity differs in two respects from the value listed in NBS Handbook 52 as "Maximum permissible amount of radioisotope in total body for continuous exposure," commonly referred to as "body burden" or "body limit":

(a) these values are based on a single brief exposure, whereas HB 52 values are based on continuous exposure (8 hours per day, 5 days per week).

(b) a factor is included to represent the improbability of inhaling a large amount of activity when the material has a very low specific activity.

As a consequence, a potential hazard unit is a greater number of microcuries than the conventional body burden—in most cases from 7 to 40 times as great.

This new unit is a concise characterization of the probable hazard arising from sudden release of active material. The unit on which determination of a PHU value is based is the MPI (maximum permissible intake), for short exposures, of K. Z. Morgan et al. Morgan has chosen three maximum permissible doses:

300 mr in 1 week,
15.7 r in 1 year,
150 r in 70 years.

He has calculated the amount of a given nuclide which when suddenly taken into the body would give each of the above doses in the corresponding time interval. The MPI for this nuclide is then the lowest of the three amounts so calculated. Morgan has gone through this process for each of several different ways in which radionuclides might enter the body. For the sake of simplicity, we consider only two of his cases: "Case I—Inhalation of soluble material, where the lung is not the critical organ;" and "Case IV—Inhalation of insoluble material, where the lung is the critical organ." We have also changed his permissible dose of 300 mr in one week to 1.5 r in one week, believing that this is more closely equivalent in hazard to the other doses.


12 Morgan, et al., ibid.
For isotopes of which only soluble compounds are used as sources, only Case I is considered; where the compounds are clearly insoluble, only Case IV is considered. Where there is a question about solubility, the geometric mean of Cases I and IV is used. The MPI values thus obtained are then divided by $p$, the relative probability of dispersal, to arrive finally at a single value of PHU for each nuclide.

For calculating values of MPI, one has

$$MPI = \frac{9.37 \times 10^{-3} Dm}{f T \sum (bE)(RBE) N \left[ T_r \left( \frac{-0.231}{1-e^{\frac{T_r}{T}}} \right) + \frac{-0.693 t_e}{T} \left( \frac{0.231}{1-e^{\frac{t_e}{T_b}}} \right) \right]}$$

$D$ = dose (in rem),

$m$ = mass of critical organ (grams),

$f$ = fraction of intake that reaches critical organ,

$T$ = effective half life (days) = $\frac{T_r T_b}{T_b + T}$,

$T_r$ = radioactive half life (days),

$T_b$ = biological half life (days),

$\Sigma (bE)$ = effective energy of radiation,

$(RBE)$ = relative biological effectiveness = 1 for $\beta$ and $\gamma$, 10 for $\alpha$,

$N$ = nonuniform distribution factor = 1 (except $N = 5$ when bone is the critical organ),

$t_2$ = period of exposure for dose, $D$ (three periods are considered:

$t_2 = 7$ days for $D = 1.5$ rem,

$t_2 = 1$ year for $D = 15.7$ rem,

$t_2 = 70$ years for $D = 150$ rem).

The inclusion of a factor to take into account the relative probability of dispersal is necessary with certain long-lived isotopes because of the large mass corresponding to the value of MPI calculated as above. For example, the mean MPI value calculated for Th$^{232}$ amounts to nearly 1
gram, which is an extremely improbable amount for a person to inhale in a short time. It is arbitrarily assumed that the probability of generating a dust concentration of 300 mg/m$^3$ (upper limit for dusty factory) is 0.1% of the probability of generating a dust concentration of 0.3 mg/m$^3$ (lower limit for normal city air). Further, assuming a 10-minute duration of the airborne contamination and a breathing rate of 0.02 m$^3$/min and setting the probability of being able to inhale 0.06 mg (that is, $0.3 \times 0.02 \times 10$) as 1.00, then the expression for $p$, the relative probability of dispersal, is stated as

$$p = \frac{0.06}{x} , \quad p \leq 1.00,$$

where

$$x = \text{mass in milligrams of the MPI}.$$

Now, for calculating values of PHU,

$$\text{PHU} = \frac{\text{MPI}}{p}.$$

Table I shows the number of microcuries constituting a PHU for each of many nuclides used as source material.

The intrinsic hazard associated with each source is then established as the number of PHU's it presents. For nuclides with short half lives, this number decreases as the source decays, and the labeled evaluation in PHU units must be regularly revised.

It should be emphasized that this system of hazard evaluation is only a rough means of classifying sources. The evaluation refers only to the source material and not the enclosure or packaging. It is based solely on the extreme consequences should a sudden spill occur, and does not consider the hazard resulting from possible slow leakage over a long time. It has been established that periodic checks are necessary; for the purpose of scheduling these checks, sources can be grouped in five classes. The decision as to which class a certain source is to be put into is based primarily on the number of PHU's it contains, plus an arbitrary evaluation of the mechanical integrity of the packaging. That is, if the source material is not securely confined within its holder, the source is put into a more hazardous class than indicated by PHU value alone.
Table I: List of PHU values

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Content of 1 PHU (μC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C$^{14}$</td>
<td>3,000</td>
</tr>
<tr>
<td>Na$^{22}$</td>
<td>910</td>
</tr>
<tr>
<td>Co$^{60}$</td>
<td>250</td>
</tr>
<tr>
<td>Ni$^{63}$</td>
<td>1,500</td>
</tr>
<tr>
<td>Se$^{75}$</td>
<td>1,400</td>
</tr>
<tr>
<td>Sr$^{90}$</td>
<td>11</td>
</tr>
<tr>
<td>Ru$^{103}$</td>
<td>400</td>
</tr>
<tr>
<td>Ru$^{106}$</td>
<td>40</td>
</tr>
<tr>
<td>Sb$^{124}$</td>
<td>120</td>
</tr>
<tr>
<td>Cs$^{137}$</td>
<td>630</td>
</tr>
<tr>
<td>Ce$^{144}$</td>
<td>60</td>
</tr>
<tr>
<td>Pm$^{147}$</td>
<td>690</td>
</tr>
<tr>
<td>Tm$^{170}$</td>
<td>200</td>
</tr>
<tr>
<td>Po$^{208}$</td>
<td>1.0</td>
</tr>
<tr>
<td>Po$^{210}$</td>
<td>1.4</td>
</tr>
<tr>
<td>Ra$^{226}$</td>
<td>1.2</td>
</tr>
<tr>
<td>Th$^{228}$</td>
<td>0.17</td>
</tr>
<tr>
<td>Th$^{232}$</td>
<td>1,100</td>
</tr>
<tr>
<td>U$^{238}$</td>
<td>36,000</td>
</tr>
<tr>
<td>Pu$^{238}$</td>
<td>0.062</td>
</tr>
<tr>
<td>Pu$^{239}$</td>
<td>0.050</td>
</tr>
<tr>
<td>Am$^{241}$</td>
<td>0.16</td>
</tr>
<tr>
<td>Am$^{243}$</td>
<td>0.16</td>
</tr>
<tr>
<td>Cm$^{242}$</td>
<td>1.2</td>
</tr>
<tr>
<td>Cm$^{244}$</td>
<td>0.33</td>
</tr>
</tbody>
</table>
### Table II: Hazard and Classification

<table>
<thead>
<tr>
<th>Class</th>
<th>Normal range of PHU content</th>
<th>Control schedule</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Less than 1 PHU</td>
<td>Check location and ownership of source annually</td>
</tr>
<tr>
<td>2</td>
<td>One or more PHU, but less than 1000 PHU's</td>
<td>Check location, ownership, and integrity of source annually</td>
</tr>
<tr>
<td>3</td>
<td>1000 or more PHU's</td>
<td>Check location, ownership, and integrity of source every 6 months</td>
</tr>
<tr>
<td>4&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1000 or more PHU's</td>
<td>Check location, ownership, and integrity of source every 3 months</td>
</tr>
<tr>
<td>5&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1000 or more PHU's (for unusually hazardous sources)</td>
<td>Set up control on an individual basis for each source</td>
</tr>
</tbody>
</table>

<sup>a</sup>Classes established for sources which are unusually hazardous because of inadequate confinement. An example of a Class 5 source would be a Mylar-covered Po<sub>210</sub> source of 1 mC or more, which is to be returned every 2 to 3 weeks for re-covering.
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