# RADIATION PROTECTION REQUIREMENTS FOR FABRICATING RECYCLED PLUTONIUM REACTOR FUEL*

**T. A. STEELE, A. B. SHUCK and P. K. DOHERTY†**
Argonne National Laboratory,
Argonne, Illinois

**Abstract**—A computer program was developed that calculated the dose rates from plutonium as a function of source weight, geometry, isotopic composition, age, and shielding composition and thickness. Dose rates from plutonium sources were measured and compared with the calculated values. Personnel radiation exposures were monitored during the fabrication of fuel elements containing varying isotopic compositions of plutonium. The information derived from the calculations, radiation measurements, and radiation exposures were applied to glovebox procedures for the fabrication of reactivity coefficient fuel elements. Radiation protection criteria for the fabrication of recycled plutonium are discussed.

## INTRODUCTION

Plutonium is fabricated into fuel elements and specimens for reactor research at the Argonne National Laboratory Plutonium Fuel Fabrication Facility. This facility was constructed in the late 1950's to meet Argonne's requirements for plutonium to be used in experimental reactors. Maximum fabrication flexibility, the safety of operating personnel, and the protection of the surrounding environment were concerns of prime importance.

The probability of operating personnel sustaining internal radiation exposures from plutonium at the facility was minimized by enclosing all of the process equipment in a leak-proof helium atmosphere, glovebox system,[1, 2] as illustrated in Fig. 1. To date, this system has proved effective in preventing any significant internal insult of plutonium to workers at the facility. It also has prevented any significant release of plutonium to the environment.

Commercial utilization of plutonium in power reactor fuel cycles depends on a developed capability to safely and economically process, fabricate, and use fuel elements that contain large proportions of $^{238}Pu$, $^{240}Pu$, $^{241}Pu$, and $^{242}Pu$. X, gamma, and neutron radiations from these isotopes and their daughter products, particularly $^{241}Am$ and $^{237}U$, present an external radiation hazard during fabrication. Early plutonium contained less than 10 w/o of these isotopes, but recycled power reactor plutonium will contain 20 to 60 w/o of them.

The external radiation hazard to personnel fabricating recycled plutonium in a glovebox was evaluated by the following three steps. A computer program was developed to calculate dose rates from typical isotopic mixtures of plutonium. Details of the sources and shields encountered in a fuel plate fabrication process were formulated and dose rates were calculated. Next, dose rate calculations were checked by measurements of X, gamma, and neutron radiations from sources of known isotopic composition and age. Finally, the dose rates found from the calculations and radiation measurements were used to establish fuel plate fabrication procedures. Personnel radiation exposures were examined, and radiation protection considerations for recycle plutonium fuel plate fabrication were made.

## DEVELOPMENT OF A COMPUTER PROGRAM

A computer program was developed for the calculation of neutron and gamma ray dose rates encountered in the fabrication of plutonium

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† AMU-ANL Summer Engineering Practice School Student from Purdue University, Lafayette, Indiana.

reactor fuel inside a glovebox system. Surface and shielded dose rates were calculated as a function of the weight, geometry, and isotopic composition of the source, the composition and thickness of the shielding, and the elapsed time after chemical purification of the plutonium.

The program first calculated source strengths using the Bateman equations,[3] standard decay formulae, gamma-ray energy and yield data,[4] and spontaneous fission data.[5]

The source geometry was considered next. Typical sources encountered in the fabrication process were represented by a spherical or disc shape. For each model, the dimensions of the source were calculated from weight and density of the plutonium or plutonium alloy. The distance from the source to the dose point was varied.

Next, the self-shielding factors, which allow for self-absorption of X- and gamma rays by the source, were computed for the source material.[6] Attenuation of the X and gamma flux by the shield material was calculated using expressions derived by Rockwell.[7] The X- and gamma-ray attenuations were found for 14 representative gamma-ray energies. Attenuation coefficients were taken from the data of Grodstein and Storm *et al.*[8,9] Plane monodirectional and isotropic point source build-up factors, which account for scattered gamma rays, were used for the disc and spherical sources. Build-up factors for each energy were fitted to the form

$$B = 1 + \alpha \mu t \qquad (1)$$

All of the build-up factor data were taken from Goldstein and Wilkins' work.[10]

FIG. 1. A view of the ANL fuel fabrication facility glovebox system.

The surface X- or gamma-ray dose rate, $D$, from a disc source was derived via

$$D = \frac{SB_1F_{s_2}}{A_2C} \qquad (2)$$

where $S$ = X- and gamma-ray source strength, photons/sec,
$B_1 = \frac{1}{2}$ surface area of disc source excluding edges,
$F_{s_2}$ = source build-up factor,
$A_2$ = self-shielding factor,
$C$ = conversion of gamma-ray flux to dose rate.[7]

The dose rate for a disc source through attenuating media was derived via

$$D = \frac{SB_1B_2F_{s2}}{A_2C}\left[E_1(x) - E_1(x \sec\theta)\right] \quad (3)$$

where $B_2$ = shield build-up factor,

$$x = \sum_{i=1}^{n} \mu_i t_i, \text{ for } n \text{ shield layers,}$$

$\mu$ = attenuation coefficient,
$t$ = thickness,

$$E_1(x) = \int_x^\infty \frac{e^{-t}}{t} dt$$

$\theta$ = angle formed by the center line of the source and a line from an elemental area of the source to the dose point.

Similar expressions are used for spherical sources. Dose rates were calculated for each of the fourteen energy groups and summed. The spontaneous fission rate was calculated using data from Steindler.[5]

The source strength of neutrons produced by the $(\alpha, n)$ reaction with the light elements such as aluminum was calculated from data given by Arnold.[12] Birchall suggests a factor of 1.5 for neutron multiplication in a 1 kg sphere of plutonium;[13] however, no factor was used in this calculation. Neutron intensity was assumed to be attenuated by distance alone. The total surface and distance attenuated neutron dose rate was computed using a quality factor of 10. The neutron and gamma dose rates at the surface and at a dose point were printed out for each source-shield configuration.

## SHIELDING REFERENCE DATA

The composition and densities of the shielding materials had to be known before X- and gamma-ray attenuation coefficients could be determined.

The alpha phase density of plutonium, 19.86 g/cm³, was used. Type 304L stainless steel, composed of 69% Fe, 19% Cr, 10% Ni, 1.5% Mn and less than 1% Si, has a density of 7.92 g/cm³. Helium was assumed to be a pure gas at atmospheric pressure and room temperature and having a density of $2.32 \times 10^{-4}$ g/cm³. The hoodline windows were composed of a material commercially designated CR-39. This material is chiefly allyl diglycol carbonate with a density of 1.31 g/cm³.[15] The neoprene used in the hoodline gloves has a density of 1.28 g/cm³.[14] Leaded gloves are specified in equivalent lead thickness. Lightly leaded gloves have a 0.1 mm equivalent lead thickness with a density of 1.52 g/cm³. Leaded glass has attenuation characteristics similar to tantalum and a density of 6.2 g/cm³.[16]

## FABRICATION OF REACTIVITY COEFFICIENT ELEMENTS

Several hundred plate-type plutonium fuel elements are being fabricated at Argonne National Laboratory to determine the effects of increasing amounts of $^{240}Pu$, $^{241}Pu$, and $^{242}Pu$ on reactor kinetics.[17, 18] The elements required are of the type shown in Fig. 2. They consist of Pu-1.1 w/o Al alloy plates that are sealed in tight-fitting stainless steel jackets. The flow diagram of the process for manufacturing these fuel elements is shown by Fig. 3. The purified, highly irradiated plutonium is received in the form of reduction buttons that weigh

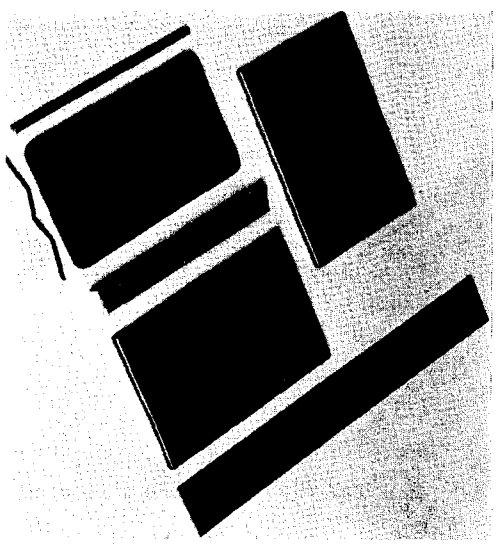

FIG. 2. Plutonium reactivity coefficient fuel element.

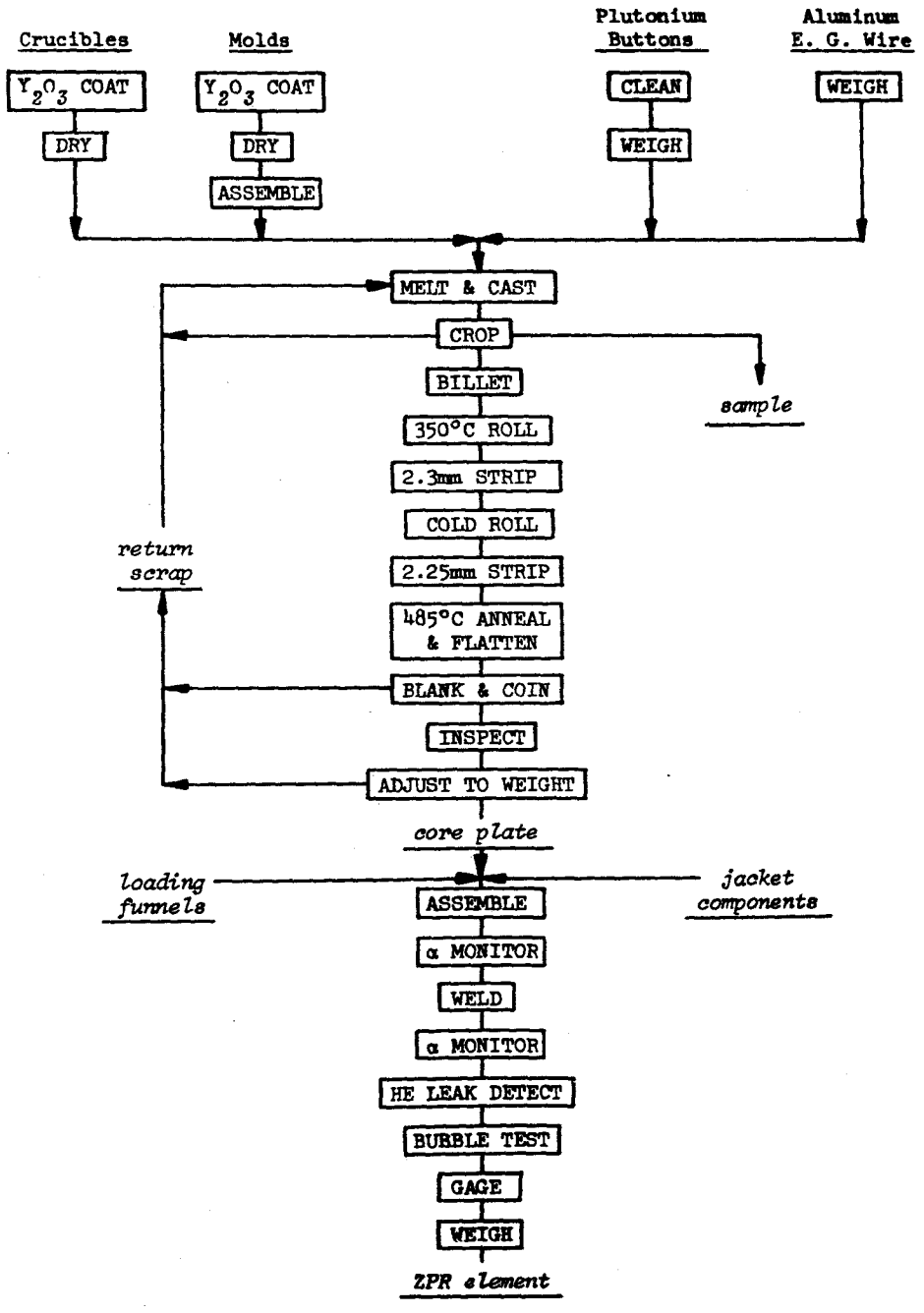


FIG. 3. Flow diagram of process for manufacturing reactivity coefficient elements.

about 2 kg each. The plates are fabricated in a helium atmosphere glovebox system, but without shielding other than that provided by the equipment.

The Pu-Al alloy is made in a vacuum induction furnace. Electrical-grade aluminum wire is placed in the bottom of an yttria-coated carbon crucible, and a broken plutonium button is placed on top of the wire. The charge is melted and heated to 950°C. It is bottom-poured into an yttria-coated carbon billet mold. After the casting cools, the furnace is opened and the billet is removed and carefully cleaned. The top is sawed off to produce a rolling billet that measures approximately 16 mm × 50 mm × 125 mm.

The billet is heated to 350°C and hot rolled from 16 mm to 2.30 mm thickness. Reductions are 15% per rolling pass between 125 mm diameter × 200 mm two-high rolls that are electrically heated to 250°C. The 2.30 mm strip is cold finished to 2.25 mm thickness. It then is annealed by heating to 485°C and flattened by pressing between steel flats.

Three sizes of core plates (measuring 2.25 mm × 45.0 mm × 23.9 mm, 2.25 mm × 45.0 mm × 49.3 mm, and 2.25 mm × 45.0 mm × 74.7 mm) are blanked and coined from strip by a combination die in a 200-tonne press. Coining pressures of 4 tonnes/cm² are used. The core plates are cleaned, adjusted to within ± 0.5 g of a nominal weight by punching holes in the plates, and inspected.

The inspected core plates are assembled in 0.3 mm thick stainless steel jackets. A spring in each jacket holds the core plate against one end. An aluminum foil funnel is used during loading of the core to protect the jacket lip from being contaminated by plutonium. The funnel is removed and the end plug is inserted. Welding is done by means of a tungsten-electrode d.c. arc process in copper chills that completely enclose the element except at the edges being joined. One-third to one-half of a standard atmosphere pressure of 85v/o He-15v/o A gas is used in the welding chamber to reduce the internal jacket pressure. The completed reactivity coefficient elements are monitored for alpha contamination, leak-detected, gaged, weighed, inspected, and packed for shipment to the reactor experimental groups.

Table 1 lists personnel exposure times associated with the fabrication of 2 kg of plutonium into reactivity coefficient elements.

## EXPOSURE CONDITION CALCULATIONS

The dose rates to the extremities were considered both in contact with the source material and at varying distances. Dose rates to the whole body were considered at varying distances. Table 2 illustrates the source-shield configurations considered.

The dose rate for each of these cases was calculated for 3 months, 6 months, 1 year, 2 years, and 5 years after plutonium separation. Table 3 gives the plutonium compositions investigated.

*Table* 1. *Exposure Times Associated with Fabrication Operations*

| Fabrication operation | Exposure time |
|---|---|
| Transfer plutonium from storage vault to glovebox system | 5 min |
| Weigh plutonium | 20 min |
| Break plutonium into pieces and weigh | 30 min |
| Transfer to furnace glovebox | 5 min |
| Alloy plutonium in furnace | 15 min |
| Cast plutonium in graphite mold | 15 min |
| Open mold and break off sprue | 1 hr |
| Roll ingot into plates | 6 hr |
| Cut and machine core plates | 4 hr |
| Clean and weigh core plates | 4 hr |
| Jacket and weld fuel element | 2 hr |
| Inspect fuel element | 1 hr |

*Table 2. Source Shield Configurations*

| Source | Source geometry | Shield |
|---|---|---|
| 2.0 kg plutonium | Spherical | 44.8 cm He, 0.95 cm CR-39 |
| 2.5 kg plutonium | Spherical | 30.4 cm He, 0.076 cm neoprene |
| 2.5 kg plutonium | Spherical | 29.5 cm He, 0.95 cm 6.2 g/cm$^3$ lead glass |
| 2.53 kg plutonium-1.25 w/o aluminum | Slab | 44.8 cm He, 0.95 cm CR-39 |
| 2.53 kg plutonium-1.25 w/o aluminum | Slab | 43.8 cm He, 0.95 cm CR-39, 0.95 cm 6.2 g/cm$^3$ lead glass |
| 71.66 g plutonium-1.25 w/o aluminum | Slab | 12.6 cm He, 0.076 cm neoprene |
| 71.66 g plutonium-1.25 w/o aluminum | Slab | 12.6 cm He, 0.076 cm lightly leaded glove |
| 71.66 g plutonium-1.25 w/o aluminum | Slab | 12.6 cm He, 0.076 cm neoprene, 0.03 cm 304L-SS |
| 71.66 g plutonium-1.25 w/o aluminum | Slab | 12.6 cm He, 0.076 cm lightly leaded glove, 0.03 cm 304L-SS |

*Table 3. Plutonium Isotopic Compositions Studied**

| Source | $^{238}$Pu | $^{239}$Pu | $^{240}$Pu | $^{241}$Pu | $^{242}$Pu |
|---|---|---|---|---|---|
| A | 0.00001 | 95.01 | 4.51 | 0.47 | 0.01 |
| B | 0.0001 | 91.15 | 8.00 | 0.80 | 0.05 |
| C | 0.002 | 80.91 | 16.69 | 2.15 | 0.267 |
| D | 0.020 | 76.68 | 20.00 | 3.00 | 0.3 |
| E | 0.030 | 72.55 | 22.16 | 4.60 | 0.666 |
| F | 1.000 | 64.00 | 20.00 | 12.00 | 3.00 |
| G | 0.040 | 62.76 | 30.00 | 6.00 | 1.20 |
| H | 2.000 | 40.00 | 30.00 | 18.00 | 10.00 |
| I | 0.100 | 34.90 | 35.00 | 10.00 | 20.00 |
| J | 0.200 | 4.80 | 25.00 | 10.00 | 60.00 |
| K | 0.300 | 0.70 | 2.00 | 1.00 | 96.00 |

* All in weight %.

Sources D, E, F, G, and H are representative isotopic compositions of recycled plutonium fuel from power reactors. Sources having isotopic compositions I, J, and K represent specially separated material to be used for physics experiments in zero power reactors.

## CALCULATED RESULTS

The computed slab surface dose rates from X- and gamma rays are illustrated in Fig. 4. The calculated neutron surface dose rates were less than 15% of the 3-month X- and gamma-ray dose rates, except for source composition K which was 22% of the 3-month dose rate.

Figure 4 shows that the surface X- and gamma-ray dose rates for plutonium more than 1 year old were primarily from the $^{241}Am$ and, therefore, a function of the $^{241}Pu$ content. Examples of calculated dose rates as a function of source geometry, weight, isotopic composition, age, source-to-dose-point distance, shielding material, and shielding thickness are illustrated in Figs. 5 through 8. Figure 5 gives the calculated total neutron and gamma dose rates at 30.5 cm through the hoodline window from a 2.5 kg plutonium sphere. The distance was established as an average exposure distance of the fabrication worker. The dose rates through the neoprene gloves from this source were nearly the same. Replacing the 0.95 cm CR-39 with 0.95 cm of 6.2 g/cm³ density leaded glass reduced the calculated 3-month dose rates by factors of 2.6 to 3.3 for isotopic compositions A, B, C, D, E, G, and I, factors of 8.5 and 9.4 for isotopic compositions F and H, and factors of 1.5 and 2.1 for isotopic compositions J and K. The important consideration in this calculation was that with the leaded glass there is no significant build-up in calculated dose rates with time after separation. The absence of build-up was due to the absorption of the low energy decay products by the leaded glass. Figures 6, 7, and 8 illustrate the dose rates to the hands from a single plutonium fuel plate under various shield configurations. Calculations indicate that no increased attenuation was gained with the use

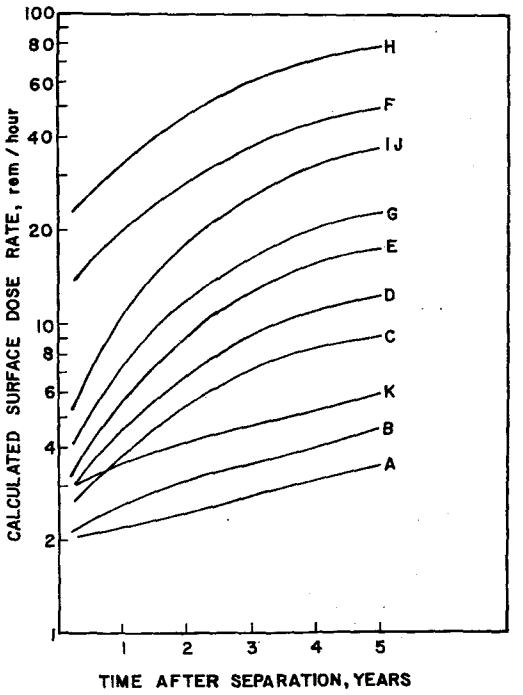


FIG. 4. Calculated X- and gamma-ray surface dose rate from a slab for various plutonium isotopic compositions.

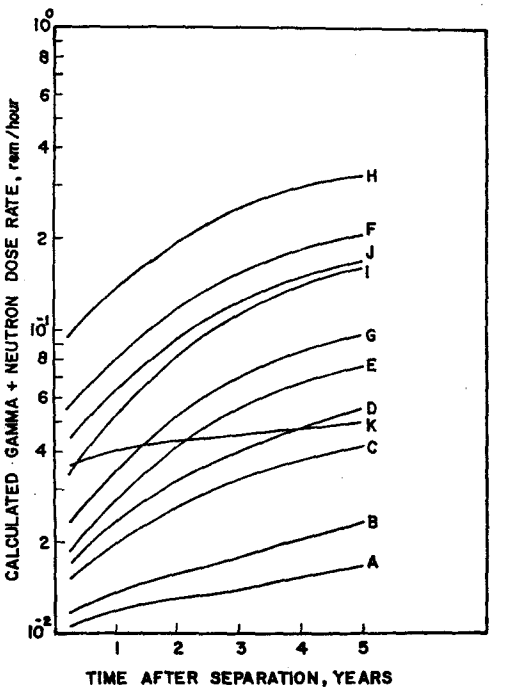


FIG. 5. Calculated total dose rate at 30.5 cm from a 2.5 kg plutonium sphere shielded by 0.95 cm CR-39.

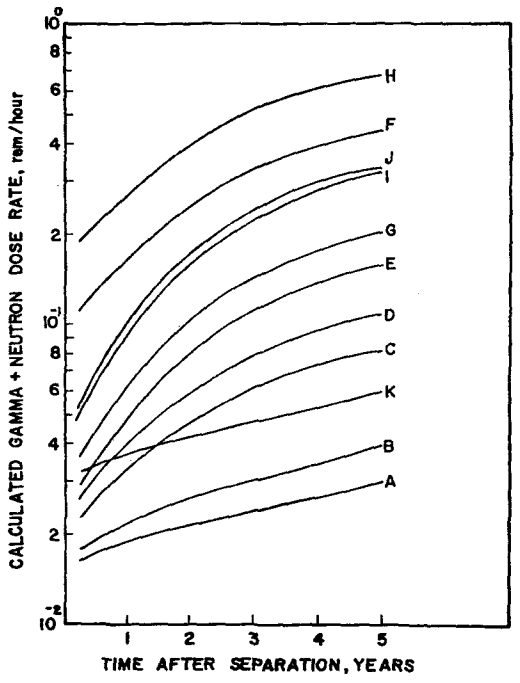


FIG. 6. Calculated total dose rate at 12.7 cm from a 71.66 g plutonium core plate shielded by 0.76 mm neoprene glove.

of lightly leaded gloves during handling of jacketed fuel elements.

## CONFIRMATION OF CALCULATED DOSE RATES

*Preparation of Samples*

Specimens of plutonium used for surface exposure rate measurements were prepared by casting 25 mm × 32 mm × 3.18 mm and 25 mm × 32 mm × 1.59 mm plates. These plates were pure plutonium with less than 1% impurities. Samples of plutonium for the shielded dose rate measurements were of two basic geometries: (1) a disc source approximately 10 cm in diameter and 2.5 cm thick, and (2) a fuel core plate 4.5 cm × 4.9 cm × 0.32 cm. These sources were typical of the ones encountered during fuel element fabrication.

The surface dose-rate samples were placed in a 63 mg/cm² vinyl container before insertion in the extrapolation chamber.

*Surface Exposure Rate Measurements*

Surface exposure rates were measured with an ANL-developed extrapolation chamber.[19] This instrument is very similar to the devices described in refs. 20–21. The extrapolation chamber is a parallel-plate ionization chamber having a volume that can be varied. The area of the collecting electrode is 0.724 cm². The depth of the chamber can be varied from 0.04 cm to 0.25 cm. A vibrating reed electrometer measures the current generated in a predetermined volume. After determining and taking into account the vinyl attenuation, the current reading was converted to roentgens/hour using an electronic calibration. This calibration is checked frequently with a standard uranium source which consistently yields 0.240 ± 0.015 R/hr through a 6 mg/cm² aluminum alpha absorber.

Measurements of the surface exposure rates of the plutonium specimens were made, and the build-up in intensity was observed as a function of time after plutonium separation.

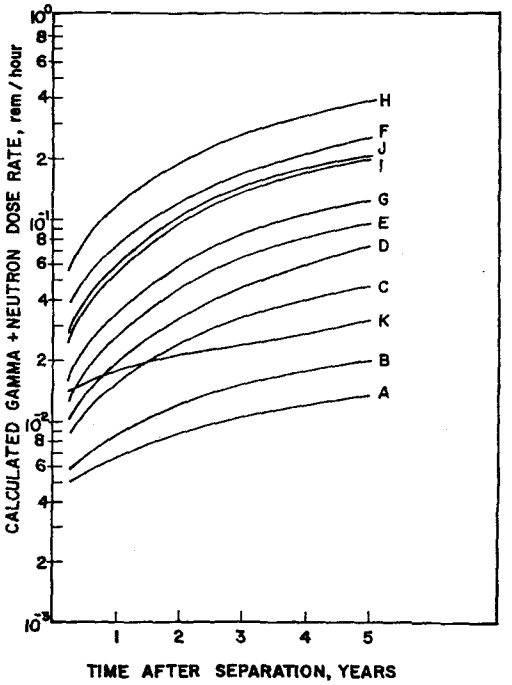


FIG. 7. Calculated total dose rate at 12.7 cm from a 71.66 g plutonium core plate shielded by 0.76 mm lightly leaded neoprene glove.

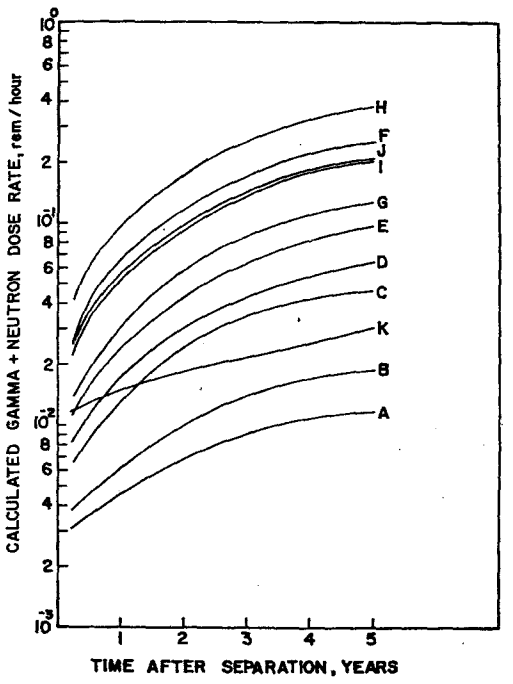


FIG. 8. Calculated total dose rate at 12.7 cm from a 71.66 g plutonium core plate jacketed by 0.3 mm stainless steel and shielded by 0.76 mm neoprene gloves.

Comparison of the measured exposure rates from specimens having compositions C and E yielded X- and gamma-ray surface exposure rates ± 25% of the calculated values. Table 4 illustrates typical measurements made with the extrapolation chamber.

*Shielded Radiation Measurements*

Measured exposure rates from the disc and plate sources in various shielding configurations were made. The X- and gamma-ray measurements were made with National Bureau of Standards calibrated R-meters, standard ion chamber instruments, and personnel dosimeters which were calibrated to the radiation field produced by the plutonium in the glovebox system. Neutron dose rate measurements were made with a 25 cm diameter, tissue equivalent, polyethylene, neutron dosimeter calibrated in mrem/hr. Measured neutron dose rates from the small single plate were within ± 25% agreement with the calculated dose rates for the isotopic compositions A, C, and E. The X- and gamma-ray exposure rates from the small plate also were in agreement with the calculated values ± 30%. Radiation measurements from the 2.5 kg disc source with isotopic composition E one year after separation was 50 mR/hr X and gamma and 5 mrem neutron at 30.5 cm through CR-39. This measurement can be compared to the calculation for the spherical source. The variations in dose rates can be attributed to differences in the geometry of the compared sources and self-shielding.

*Table 4. Extrapolation Chamber Measurements*

| Source isotopic weight % | | | | | Source weight grams | Time after purification (approx.) | Surface exposure rate R/hr |
|---|---|---|---|---|---|---|---|
| $^{238}Pu$ | $^{239}Pu$ | $^{240}Pu$ | $^{241}Pu$ | $^{242}Pu$ | | | |
| 0.02 | 80.91 | 16.67 | 2.15 | 0.27 | 30.2 | 8 months | 2.92 ± 0.17 |
| | | | | | | 9 months | 3.34 ± 0.2 |
| | | | | | | 11 months | 3.7 ± 0.22 |
| | | | | | | 1 year | 3.81 ± 0.23 |
| 0.034 | 72.55 | 22.16 | 4.62 | 0.67 | 21.6 | 10 months | 4.5 ± 0.27 |
| | | | | | | 11 months | 5.0 ± 0.3 |
| 0.034 | 72.55 | 22.16 | 4.62 | 0.67 | 40.9 | 8 months | 4.1 ± 0.25 |
| | | | | | | 9 months | 4.55 ± 0.27 |
| | | | | | | 10 months | 4.95 ± 0.3 |
| | | | | | | 11 months | 5.44 ± 0.33 |

## WHOLE BODY AND EXTREMITY RADIATION EXPOSURE EXPERIENCED DURING PLUTONIUM FABRICATION

Past experience has indicated that whole-body radiation exposure is the limiting consideration during plutonium fabrication at the ANL Plutonium Fuel Fabrication Facility. The whole body of the fabrication worker is monitored with a film badge with aluminum, silver, and cadmium filters containing a Dupont 558 film packet and a Kodak NTA neutron film. A secondary device, the Shonka tissue-equivalent dosimeter, is used in conjunction with the film badge for day-to-day and comparison measurements of the fabrication worker's exposure. The neutron film in the badge is not a good indicator of neutron exposure due to the low intensity and energy of the Plutonium Fabrication Facility's neutron background.[23] Neutron exposures are assigned as a function of the worker's activities and the associated neutron backgrounds.

Hand exposures, previous to this year, were monitored by wrist badges only. Correlation of wrist/hand exposures have been made, and a 1/3 ratio was found.[24] A method of using thermoluminescent dosimeters to determine hand exposures has been developed.[25, 26] The dosimeters are worn on the fingers of operating personnel, and the hand exposures are determined through calibration of the dosimeters with the plutonium handled at the time of the exposures. Results from these dosimeters compared to wrist badges indicate that the 1/3 wrist/hand ratio is conservative.

Personnel exposures are the greatest when fabrication workers are handling plutonium sources that have large surface areas and weigh more than 1 kilogram. The highest radiation exposures encountered during the fuel fabrication process are those received during the casting and weighing operations. The amount of plutonium fabricated at ANL each year and its isotopic compositions are given in Table 5. Whole body and hand exposures during the casting operation are listed. Hand exposures listed as beta are considered to be nonpenetrating scattered X-rays with energies below 12 keV. Administrative guidelines on radiation exposure are 5 rem/year for the whole body, 75 rem/year to the extremities, and 30 rem/year to the skin of the whole body.

*Table 5. Total Radiation Exposure Experienced by Personnel During Plutonium Casting Operation*

| Year | Kilograms plutonium fabricated | Isotopic composition weight % Pu | | | | Personnel exposure | |
|---|---|---|---|---|---|---|---|
| | | $^{239}Pu$ | $^{240}Pu$ | $^{241}Pu$ | $^{242}Pu$ | Whole body | Hand |
| 1963 | 37 | 95 | 4.5 | 0.4 | 0.01 | 1 rem (1 individual) | 14 rad $\beta$ 2.5 rem X, $\gamma$ |
| 1964 | 23 | 91 | 8 | 0.8 | 0.05 | 3 rem (1 individual) | 11 rad $\beta$ 5 rem X, $\gamma$ |
| 1965 | 21 | 91 | 8 | 0.8 | 0.05 | 3 rem (1 individual) | 4 rad $\beta$ 1.5 rem X, $\gamma$ |
| | 3.1 | 88 | 10 | 1.4 | 0.03 | | |
| | 1 | 73 | 22 | 4.6 | 0.7 | | |
| 1966 (6 months) | 25 | 91 | 8 | 0.8 | 0.05 | 5 rem (2 individuals) | 10 rad $\beta$ 2.7 rem X, $\gamma$ |
| | 8.5 | 90 | 9 | 1.1 | 0.05 | | |
| | 5.3 | 88 | 10 | 1.4 | 0.05 | | |
| | 23 | 73 | 22 | 4.6 | 0.7 | | |

## RADIATION PROTECTION CONSIDERATIONS FOR GLOVEBOX FABRICATION OF RECYCLED PLUTONIUM

From Table 5, it can be seen that the present problem is the whole body exposure. Hand exposures are less than 25% of the maximum guides. These exposures were all through the CR-39 windows and nonleaded gloves.

Comparing Fig. 5, which are the calculated dose rates from a spherical 2.5 kg plutonium source through CR-39, with the computed dose rates through 0.95 cm of 6.2 g/cm$^3$ lead glass, the calculated lead glass shielded dose rates from isotopic compositions B through H are reduced to levels below that from composition A through CR-39. In addition, there is no dose rate build-up with increasing source age. Neutrons then become the predominant source of radiation exposure. This shielding configuration centers attention on the dose rates through the lightly leaded gloves, which increases with source age.

Lightly leaded gloves generally reduce the X- and gamma-ray dose rates by a factor of 2. Heavy leaded gloves are 3.5 times as effective in reducing the exposure rates; however, they are too cumbersome and restrict manipulation with the fingers. Direct contact exposure to the hands through lightly leaded gloves for plutonium sources with compositions F and H must be limited. Direct hand contact with plutonium sources having compositions D through J would have to be limited if processed 5 years or more after separation. Processing at intermediate times after separation would have to be done under carefully established guidelines to keep extremity exposures below radiation protection exposure limits.

Fabrication of large amounts, greater than 100 kg/year, of recycled plutonium fuel in a glovebox system will require shielding and close surveillance of personnel exposures. Fabrication of small amounts, less than 10 kg/year, of material with compositions E, F, G, H, I, and J would be possible in a partially shielded glovebox system.

Close surveillance of personnel exposures will be required for rotation of personnel to tasks calculated to keep their radiation exposures within prescribed limits. The fabrication of large amounts of recycled plutonium per year will require many personnel available for rotation, and glovebox fabrication may not be economically feasible due to the number of personnel required. Under those circumstances, a remote fabrication process would have to be developed.

## CONCLUSION

Radiation exposures of personnel who fabricate plutonium fuels in an unshielded glovebox system are not a serious radiation protection problem when the plutonium contains less than 5 w/o of $^{240}$Pu, $^{241}$Pu, and $^{242}$Pu. Some radiation exposure difficulty is encountered during glovebox fabrication in the 5 to 10 w/o range. Increasing difficulty in minimizing radiation exposures is encountered during glovebox fabrication of plutonium containing greater than 10 w/o of the higher isotopes.

Exposure of personnel to radiation from recycled plutonium fuel can be minimized during glovebox fabrication by the following measures:

1. Early fabrication after chemical separation.
2. Shielding applied to equipment within the gloveboxes and the glovebox surfaces.
3. Use of leaded glass for the glovebox windows.
4. Immediate removal of plutonium residues from the glovebox system.
5. Use of lightly leaded gloves and mechanical techniques for handling the plutonium.
6. Monitoring of extremity and whole body exposures to enable rotation of personnel for tasks having high exposure rates.
7. Planning fabrication procedures to reduce exposure times to a minimum.
8. Use of shielded temporary storage areas in the glovebox system.
9. Knowledge of plutonium isotopic compositions, light element analysis, and time after plutonium separation.

Some of those precautions may be neither practical nor economical for extensive and continuing fuel fabrication operations. In such cases, it will be necessary to minimize exposures of personnel to radiation by automated fabrication and inspection techniques.

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