Source Efficiency Calculations for ^{137}Cs Irradiators

by
R. A. Libby

September 1977

Prepared for the Energy Research
and Development Administration
under Contract EY-76-C-06-1830

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

The views, opinions and conclusions contained in this report are those of the contractor and do not necessarily represent those of the United States Government or the United States Energy Research and Development Administration.

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Under Contract EY-76-C-06-1830

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy \$____; Microfiche \$3.00

*Pages	NTIS Selling Price
001-025	\$4.50
026-050	\$5.00
051-075	\$5.50
076-100	\$6.00
101-125	\$6.50
126-150	\$7.00
151-175	\$7.75
176-200	\$8.50
201-225	\$8.75
226-250	\$9.00
251-275	\$10.00
276-300	\$10.25

3 3679 00062 4835

SOURCE EFFICIENCY CALCULATIONS FOR ^{137}Cs
IRRADIATORS

by
R. A. Libby

September 1977

BATTELLE
PACIFIC NORTHWEST LABORATORIES
Richland, Washington 99352

SUMMARY

The efficiency of radiation sources used for radiation treatment is important in the overall economics of irradiators. This report examines design optimization for a Cesium-137 (^{137}Cs) radiation source. The initial source design used is currently being fabricated at the Waste Encapsulation and Storage Facility (WESF). Although the current source was intended for long term storage and isolation of the cesium, it has potential for use as an irradiator.

Modifications to the source which were examined include:

- Source Diameter - The optimum cylinder diameter is 1 in.
- Wall Thickness - The optimum stainless steel wall thickness is about 0.1 in. Thicker walls will reduce source efficiency, while thinner walls increase the likelihood of wall failure.
- Cesium Product Form - A cesium-titanate ceramic combines the advantages of good source efficiency with low solubility and low leachability.

The cost to modify the present WESF facility does not appear to justify these design changes. However, new facilities could incorporate this design to obtain optimum source efficiency.

CONTENTS

SUMMARY.	iii
LIST OF FIGURES.	v
LIST OF TABLES	vi
INTRODUCTION	1
CONCLUSIONS.	2
PRESENT CAPSULE DESIGN	2
THEORY	4
CALCULATIONS	7
DESIGN MODIFICATIONS	11
REFERENCES	16

LIST OF FIGURES

1	WESF Capsule.	3
2	Dose Rate From Cesium Chloride Source - Midplane. .	8
3	Dose Rate From Cesium Chloride Source in Water. . .	9
4	Dose Rate From Cesium Chloride Source in Air. . . .	10

LIST OF TABLES

1	WESF Cesium Chloride Capsule Characteristics.	3
2	Measured Radial Dose Rates From Cesium Chloride Source.	4
3	Dose Rates From Cesium Chloride Sources	9
4	Cylinder Efficiencies	12
5	Annular Cylinder Efficiency	13
6	Plate Source Efficiency	14
7	Compound Density.	14
8	Source Efficiency	15

INTRODUCTION

Radiation treatment can be used beneficially in the treatment of food⁽¹⁾ and the thermal radiation of sewage sludge⁽²⁾ and medical products.⁽³⁾ Potential sources of radiation include electron accelerators, ^{60}Co , which is produced in reactors and ^{137}Cs , which is recovered from the reactor fuel wastes.

The Waste Encapsulation and Storage Facility (WESF) currently operated by Rockwell Hanford Operations produces sealed capsules of either radioactive cesium chloride or strontium fluoride.⁽⁴⁾ The purpose of the WESF plant is to encapsulate the radioactive cesium and strontium which is recovered from the aqueous wastes generated from the reprocessing of reactor fuel elements at the Hanford Site. The encapsulation of these elements is an initial step in the management of these nuclear fuel wastes.

The radioactive compounds are placed in capsules designed for safe long term storage. The desired characteristics for the capsule are good heat dissipation, thick capsule walls, and a size large enough to reduce the number of capsules needed to contain the required quantity of compound. The cesium product form selected was based on chemical process characteristics.

Since the original CsCl capsule was designed for storage rather than an irradiator, it seemed possible that the capsule design could be improved for use as an irradiator. The economics of irradiators are dependent on the efficiency of the radiation source; hence, a significant increase in the source efficiency would result in a significant improvement in irradiator economics. Because of this, studies were made for the Nuclear By-Product Utilization Program sponsored by the Department of Energy. This paper describes the types of design changes examined and gives the effect of these changes on the source efficiency.

CONCLUSIONS

The results of these source efficiency calculations indicate that an increase in the efficiency of the WESF cesium capsules is possible. This would require changes in the cylinder diameter and wall thickness. To reduce the possibility of environmental contamination when the capsules are used in irradiators, it may be desirable to change the cesium compound form especially if capsule wall thickness is decreased. Compound form change would reduce slightly the source efficiency. The net efficiency change would be an increase from 60% for the present design to 72% for the titanate ceramic in a 1-in. diameter source with 0.1-in. wall.

To evaluate the cost-effectiveness of the proposed changes, the extra expense of more sources with increased handling and fabrication costs and the cost of WESF facility modifications need to be examined. Also, the technical feasibility of such process changes must be considered. At this point, the costs that would be incurred in increasing source efficiency by 1/5 (60% to 72%) do not appear to be justified.

Before WESF production is committed to a new Cs capsule design and product form, additional work in capsule design and cost analysis is recommended. Capsule design should be made compatible with irradiator facility design. This design analysis effort would have to evaluate not only the dose rate to the material undergoing irradiation, but also biological shielding necessary to protect the operators and the public.

PRESENT CAPSULE DESIGN

The WESF cesium capsule is a double-walled stainless steel cylinder. A view of the capsule is shown in Figure 1 and the capsule characteristics are given in Table 1.

FIGURE 1. WESF Capsule

TABLE 1. WESF Cesium Chloride Capsule Characteristics

DIMENSIONS

Inner Capsule:	316-L stainless steel
	0.095-in. wall thickness
	2.250-in. outside diameter
	19.725-in. total length
	0.400-in. total cap thickness

Outer Capsule:	316-L stainless steel
	0.109-in. wall thickness
	2.625-in. outside diameter
	20.775-in. total length
	0.400-in. total cap thickness

DENSITY CsCl	2.47 g/cm ³
--------------	------------------------

QUANTITY OF ¹³⁷ Cs	48-49 wt%
-------------------------------	-----------

IMPURITIES	4-6 wt%
------------	---------

HEAT GENERATION	300 watts
-----------------	-----------

RADIOACTIVITY	70,000 Ci ¹³⁷ Cs
---------------	-----------------------------

Dosimetry measurements were performed on one of the WESF cesium capsules to serve as a benchmark for the calculations. The experimental dose rates are listed in Table 2. These measurements were made with thermoluminescent dosimeters (TLD's). TLD-700 (LiF) chips were placed at the mid-plane of the capsule. A 10.3-minute exposure was made and a control set of TLD's was used to give a true 10.3-minute exposure.

TABLE 2. Measured Radial Dose Rates From Cesium Chloride Source

<u>Distance from Surface of Source, cm</u>	<u>Dose Rate, R/hr</u>
20	302,000
30	168,900
50	55,300

THEORY

The computer code used for dose rate calculations was QAD-P5A.⁽⁵⁾ This is a "point-kernel" code. It provides the uncollided gamma flux density, dose rate, and energy deposition rate which result from a point-by-point representation of a volume distributed radiation source. The volume source is divided into a large number of point isotropic sources and the traversal distances through each material are calculated for each point source. Based on the energy dependent attenuation for each material, the uncollided gamma flux density at a receiver point from a source point is calculated⁽⁶⁾ by

$$\phi(R) = S \frac{e^{-\mu(E)R}}{4\pi R^2} \quad (1)$$

where

S = source strength for the source point (γ /sec)

$\mu(E)$ = linear attenuation coefficient at the initial energy

$e^{-\mu(E)R}$ = material attenuation factor: i.e., the probability that a gamma of energy E travels a distance R without a collision.

$4\pi R^2$ = geometric attenuation for point source.

Our version of QAD-P5A uses the gamma interaction coefficients of Storm and Israel⁽⁷⁾ and Berger's⁽⁸⁾ energy fluence-to-exposure conversion factors.

It is important to realize that $\phi(R)$ in equation (1) is the uncollided flux density. This approximates the total flux density only when scattered gammas are completely removed from the radiation beam which is effectively realized only for thin shields. For thick shields, the probability increases that multiple collisions will occur with gammas scattering to the receiver point giving flux densities higher than those calculated by Equation (1).

Calculation of the scattered flux density is complex and so is handled by introducing a buildup factor which increases the flux density to account for scattered gamma rays. This buildup factor is a function of the shield material, gamma energy, and the quantity (i.e., flux density or dose) being calculated. Hence

$$B = \frac{[\text{property of total flux density at } R]}{[\text{same property of uncollided flux density at } R]}$$

Now

$$\phi_T(R) = B(\mu R) S \frac{e^{-\mu(E)R}}{4\pi R^2} \quad (2)$$

where

$B(\mu R)$ = flux density buildup factor

$\phi_T(R)$ = total flux density.

Similar techniques are used in QAD-P5A where the buildup factors are based on the Goldstein and Wilkins moments method of infinite homogeneous media.⁽⁹⁾ The Goldstein-Wilkins data are fitted by a polynomial expansion whose simplified form is

$$B_i(\mu R) = \beta_0 + \beta_1 \mu R + \beta_2 (\mu R)^2 + \beta_3 (\mu R)^3 \quad (3)$$

where

$B_i(\mu R)$ = the buildup factor for the i th energy group at μR mean free paths.

$\beta_0, \beta_1, \beta_2, \beta_3$ = energy dependent coefficients from polynomial fits to Goldstein-Wilkins data.

When alternate layers of different materials are part of a shield, additional problems occur. Because the gamma ray spectrum changes with penetration in a medium (due to absorption and scattering), the emergent spectrum is dependent on the arrangement of the shielding layers. QAD-P5A allows the selection of one of eight different buildup factors:

- H₂O Dose Buildup Factor
- Al Dose Buildup Factor
- Fe Dose Buildup Factor
- Pb Dose Buildup Factor
- H₂O Energy Absorption Buildup Factor
- Al Energy Absorption Buildup Factor
- Fe Energy Absorption Buildup Factor
- Pb Energy Absorption Buildup Factor.

For the capsule itself, the iron buildup factor was selected. The actual buildup factor used is then determined from a polynomial fit for the total μR using the constants for iron in equation (3). In cases where the dose rate was calculated for the capsule in water, an additional case was made using water buildup factors. The iron buildup factor was then used for points within the capsule while the buildup factor for points in the water region was found by

$$B = B_r^{\text{Fe}} (B_R^{\text{W}} - B_r^{\text{W}}) \quad (4)$$

where

B_r^{Fe} = iron buildup factor at the outside capsule radius

B_R^{W} = water buildup factor at R in water region

B_r^{W} = water buildup factor at the outside capsule radius.

While equation (4) is a very rough approximation, it is useful and reasonably accurate for similar cases. It is much simpler than other techniques used to obtain multiple region buildup factors. The only cases in which this technique is important are the water media dose rates. For air, the buildup is small and the efficiency calculations are taken at the surface of the source.

Considerable detail has been provided in the discussion of buildup because it is important in the efficiency results that follow; the effect of the buildup factor is also significant. At the outside of the present capsule design, the buildup factor is approximately 1.5 and with the capsule in water at 100-cm depth it is 37. Thus at the surface of the capsule, one-third of the dose is from scattered gamma rays while after 100 cm of water all but 3% of the dose is from scattered gamma rays. In addition, the buildup factor influences the source efficiency which tempers the effect of any change in capsule design.

QAD-P5A accepts boundary surface equations which fit the form

$$AX^2 + XX_0 + BY^2 + YY_0 + CZ^2 + ZZ_0 - k = r \quad (5)$$

As only cylinders and planes are required to model the capsule geometry, an exact representation is possible. The model used for all designs consisted of three regions

- source region (e.g. CsCl at the expected density)
- capsule wall (stainless steel whose thickness equals the total wall thickness)
- outside medium (water or air).

The point source distribution was chosen such that increasing the number of source points resulted in no significant change in the calculated dose rates. This ensures that the error in dose due to the finite distribution of source kernels is less than 5%.

CALCULATIONS

The calculated dose rates from the present WESF capsule are given in Figures 2 to 4. In Figure 2, the dose rates in air and water are plotted for radial distances up to 100 cm from the center line of the source. In Figures 3 and 4 the dose rates are plotted along several radial and axial traverses, again in both water and air.

FIGURE 2. Dose Rate From Cesium Chloride Source - Midplane

The dosimetry measurements from Table 2 agree quite well with the calculated dose rates. The experimental dose rates are listed in Table 3 along with the calculated values from Figure 2 air values. Due to the interpolation required for the 50-cm value, a 10% error is possible at this point.

Additional comparisons were made with dose rates estimated by RHO (Rockwell Hanford Operations formerly Atlantic Richfield Hanford Co.,)⁽⁴⁾ and from data in the Cesium Data Sheets.⁽¹⁰⁾ The RHO curves are difficult to interpolate accurately for a distance as small as 100 cm, but the calculated dose rates in Table 3 are very close. In the Cesium Data Sheets a spherical source of 300 thermal watts with 1 cm of iron shielding gives a dose rate of approximately 10^7 mrad/hr at 100 cm. For the WESF geometry with 1 cm of iron shielding QAD-P5A calculates a dose rate of 1.4×10^7 mrad/hr at 100 cm. Some difference can be attributed to reduced self shielding for the WESF cylindrical capsule compared to the spherical model used in the Cesium Data Sheets.

FIGURE 3. Dose Rate From Cesium Chloride Source In Water

TABLE 3. Dose Rates From Cesium Chloride Sources

<u>Distance from Surface of Source, cm</u>	<u>Measured, R/hr</u>	<u>Calculated, R/hr</u>
20	302,000	300,000
30	168,900	160,000
50	55,300	68,000

FIGURE 4. Dose Rate From Cesium Chloride Source in Air

DESIGN MODIFICATIONS

The term efficiency is used to describe and compare the different source designs. For these calculations, efficiency is defined as the ratio of the dose rate at the capsule surface with attenuation in the source region and capsule wall to the dose rate at the surface without attenuation in the source region and capsule wall. This definition was originally used in similar studies at Sandia Laboratories. There is no buildup factor applied to the dose rate calculation with no attenuation since no attenuation implies that there are no scattered gamma rays. If the buildup factor was not applied to the calculation made with attenuation, the result would be the efficiency for the uncollided gamma rays. Because the scattered gammas also contribute significantly to the dose rate, and in turn the source efficiency, the buildup factor must be included. For simple comparisons between various source designs, one might suspect the buildup factor would not be needed; however, changes in efficiency caused by modifications in the self shielding or wall attenuation are magnified when the buildup factor is not used. Also, it should be noted that the use of the dose buildup factor may tend to slightly overestimate the biological effectiveness since real efficiency is more related to energy transmission than to dose rate.

Two characteristics of the capsule affect its efficiency as an irradiator. These are the geometry of the capsule and the form of the cesium product. The source geometry parameters include the diameter, wall thickness, and shape. Included in the analysis to ascertain the potential improvements in capsule design were:

- the effect of wall thickness
- the effect of cylinder diameter
- the effect of an annular cylinder design
- the effect of a plate source design.

Decreasing the wall thickness would obviously result in reduced attenuation in the wall. Because long term storage is not required in an irradiator, thinner walls are possible, but this might require a change in

product form because of the relatively high water solubility of CsCl. Reducing the cylinder diameter would result in reduced self shielding (or attenuation within the source material itself). Similarly, it was thought that making the source an annular cylinder with a void space in the center would place source material closer to the capsule surface and reduce self shielding. Also such a design would require fewer production changes in WESF. Finally, changing the source to a flat plate might make irradiator design simpler.

The efficiencies for cylinders with various radii and wall thicknesses are listed in Table 4. The highest efficiencies are possible with cylinders having the smallest diameter and the thinnest wall as expected. However, since the number of capsules required for a given volume of compound varies inversely with the square of the diameter, an effective lower limit is reached for the smallest practical diameter. In addition, fabrication and source handling are easier with a few large sources rather than a large number of small irradiators. Evaluation of these factors indicates that the cost effective design is a cylinder with a diameter of approximately 1 in. with 0.1-in. wall thickness. Reducing the diameter to 0.5 in. results in only a 4% increase in efficiency but requires the handling and fabrication of four times as many sources. A minimum wall thickness of 0.1-in. is necessary for encapsulation.

TABLE 4. Cylinder Efficiencies

Source		Efficiency, %	Efficiency Increase Over Present Design, %
CsCl Diameter, in.	Wall Thickness, in.		
2.06	0.204	60	0 ^(a)
2.06	0.100	69	15
1.0	0.100	77	28
1.0	0.204	67	12
0.5	0.204	71	18

a. Present Capsule Design

Due to the reduction in self shielding which might be possible with an annular cylinder source geometry, calculations were also made for annular cylinders (2.625-in. OD, 0.2-in. clad); these results are summarized in Table 5. Apparently efficiency is not increased by using an annular geometry. This is probably due to an increase in the absorption in the wall from the larger wall-to-source volume ratio with thin annular regions. The ratio of source-to-clad volume decreases faster with a reduction in radius for annular regions than for cylindrical regions.

TABLE 5. Annular Cylinder Efficiency

<u>Radial Thickness, in.</u>	<u>Efficiency, %</u>
1.0	60
0.5	60
0.3	61

Calculations for a plate source geometry, summarized in Table 6, are based on a 40-cm square plate with a 0.1-in. SS wall thickness. The edge effects for the finite-sized geometry are more important for plate sources than for cylinders. The value at the wall surface approximates the efficiency at any location for an infinite plate source. Since any practical irradiator will be finite in size with a limiting distance over which irradiation will occur, these efficiency values are lower limits. As much as a 10% efficiency increase is possible for smaller irradiators. Compared with cylindrical sources, the efficiencies show no worthwhile increase, thus no significant gains are realized by switching to a plate source geometry. The only reason to change the design to a plate source would be to simplify irradiator fabrication, but this is offset by the major WESF equipment modifications which would be required.

TABLE 6. Plate Source Efficiency

<u>Source Thickness, cm</u>	<u>Efficiency, %</u>
0.5	58
1.0	59
2.0	58

Sandia Laboratories has an ongoing program on the thermoradiation of sewage sludge using radioactive cesium.^(2,11) Since the product form used in WESF (CsCl) has a high solubility in water (2 kg/liter), a small leak in a source capsule could cause contamination. Sandia has expressed interest in isolating the radioactive cesium in a high temperature/low leachability compound such as a zeolite or stable ceramic. Table 7 lists the compounds of interest, the bulk density, and the cesium density for each. The bulk densities are from a Sandia Laboratory report⁽¹¹⁾ except for cesium chloride which is from RHO estimates⁽⁴⁾ for the WESF capsule.

TABLE 7. Compound Density

<u>Compound</u>	<u>Density</u>	
	<u>g compound/cm³</u>	<u>g Cs/cm³</u>
Cs ₂ Ti ₄ O ₉	4.0	1.8
Cs ₂ Nb ₅ O ₁₁	4.7	1.6
Cs ₂ Zr ₄ O ₉	4.5	1.6
Cs ₈ (Al ₈ Si ₄₀ O ₉₆)	2.5	0.7
CsCl	2.47	1.96

Table 8 lists the efficiencies and dose rates at the clad surface for sources of the various compounds. The source geometry is the same for all compounds (diameter of 1.0 in. with 0.1 in. SS clad) the highest efficiency occurs with zeolite and cesium chloride. In all cases the dose rate is normalized to the present WESF cesium content. In comparing these dose rates, the titanate has the highest surface dose rate except for cesium

chloride. The low cesium density in the $\text{Cs}_8(\text{Al}_8\text{Si}_{40}\text{O}_{96})$ zeolite reduces the dose rate considerably and thus would require many additional sources for the same level of irradiation.

TABLE 8. Source Efficiency

<u>Compound</u>	<u>Efficiency, %</u>	<u>Dose Rate, R/hr At Clad Surface</u>
$\text{Cs}_2\text{Ti}_4\text{O}_9$	72	1.46×10^6
$\text{Cs}_2\text{Nb}_4\text{O}_{11}$	69	1.26×10^6
$\text{Cs}_2\text{Zr}_4\text{O}_9$	70	1.28×10^6
$\text{Cs}_8(\text{Al}_8\text{Si}_{40}\text{O}_{96})$	77	0.62×10^6
CsCl	77	1.76×10^6

REFERENCES

1. W. E. Sande and R. A. Libby, Potential Sources for the Radiation Treatment of Food. BNWL-2095, Battelle, Pacific Northwest Laboratories, Richland, WA, 1976.
2. H. D. Sivinski, "Treatment of Sewage Sludge with Combinations of Heat and Ionizing Radiation (Thermoradiation)." Proceedings from a Symposium on Radiation for a Clean Environment, IAEA, Munich, March 17-21, 1975.
3. C. A. Trauth and H. D. Sivinski, "The Synergistic Effects of Heat and Irradiation Treatment (Thermoradiation) in the Sterilization of Medical Products." Proceedings IAEA Symposium on Ionizing Radiation for Sterilization of Medical Products and Biological Tissues, Bombay, India, December 9-13.
4. J. R. LaRiviere, Radioactive Waste Encapsulation and Storage Facility. ARH-SA-115, Atlantic Richfield Hanford Company, July 1972.
5. R. E. Malenfant, QAD: A Series of Point-Kernel General Purpose Shielding Programs. LA-3573, Los Alamos Scientific Laboratory, April 1967.
6. N. M. Schaeffer, Reactor Shielding for Nuclear Engineers. TID-25951, USAEC, 1973.
7. E. Storm and H. I. Israel, Photon Cross Sections from 0.001 to 100 MeV for Elements 1 through 100. LA-3753, Los Alamos Scientific Laboratory, November 1967.
8. H. Goldstein, Fundamental Aspects of Reactor Shielding. Addison-Wesley Publishing Co., Inc., Reading, Massachusetts, 1959, p. 17.
9. H. Goldstein and J. E. Wilkins, Calculation of the Penetration of Gamma Rays. NYO-3075, 1954.
10. S. J. Rimshaw and E. E. Ketchen, Cs-137 Data Sheets. ORNL-4186, Oak Ridge National Laboratory, December 1967.
11. Progress Report - Beneficial Uses Program Period Ending December 31, 1975. SAND-76-0065, Sandia Laboratories, Albuquerque, NM, February 1976.

DISTRIBUTION

NO. OF
COPIES

OFFSITE

- 1 ERDA Chicago Patent Attorney
9800 S. Cass Avenue
Argonne, IL 60439
A. A. Churm
- 1 ERDA Division of Biomedical and Environmental Research
Washington, DC 20545
J. N. Maddox
- 2 ERDA Division of Waste Management, Production and Reprocessing
Washington, DC 20545
G. W. Cunningham
C. W. Kuhlman
- 9 ERDA Nuclear Research and Applications Division
Washington, DC 20545
T. J. Dobry, Jr.
N. Goldenberg
A. P. Litman
J. J. Lombardo
W. C. Remini (3)
B. J. Rock
E. J. Wahlquist
- 1 ERDA Oak Ridge Operations Office
P. O. Box E
Oak Ridge, TN 37830
D. C. Davis, Jr.
- 2 ERDA Savannah River Operations Office
P. O. Box A
Aiken, SC 29801
R. H. Bass
T. B. Hindman
- 27 ERDA Technical Information Center

NO. OF
COPIES

- 2 Battelle Columbus Laboratories
505 King Avenue
Columbia, OH 43201
W. J. Zielenbach
W. M. Pardue
- 1 Department of the Army
Headquarters, U.S. Army
Facilities Engineering Support Agency
Fort Belvoir, VA 22060
H. Musselman
- 1 Electronics and Applied Physics Division
Building 347.3, AERE Harwell
Oxfordshire OX11 0RA
Great Britain
E. H. Cooke-Yarborough
- 1 General Atomic Company
P. O. Box 81601
San Diego, CA 92138
H. C. Carney
- 1 General Electric Company MSVD
P. O. Box 8555
Philadelphia, PA 19101
P. E. Brown
- 1 General Electric Company, Vallecitos Laboratory
P. O. Box 846
Pleasanton, CA 94566
G. E. Robinson
- 3 Los Alamos Scientific Laboratory
P. O. Box 1663
Los Alamos, NM 87544
S. E. Bronisz
R. A. Kent
R. N. Mulford

NO. OF
COPIES

- 2 Monsanto Research Corporation
Mound Laboratory (ERDA)
Nuclear Operations
P. O. Box 32
Miamisburg, OH 45342
W. T. Cave
R. Dewitt
- 1 Naval Nuclear Power Unit
Code 70
Port Hueneme, CA 93043
F. E. Rosell
- 1 Naval Facilities Engineering Command
Nuclear Power Division (FAC04N)
200 Stovall Street
Alexandria, VA 22332
A. A. Arcuni
- 1 Navy Office of the Chief of Naval Operations
Washington, DC 20390
Head, Reactor Branch
- 1 Oak Ridge National Laboratory
Oak Ridge, TN 37830
E. Lamb
- 2 Sandia Laboratory
Albuquerque, NM 87115
M. Morris
H. D. Sivinski
- 3 Teledyne Energy Systems
110 W. Timonium Road
Timonium, MD 21093
P. Dick
R. Hannah
P. Vogelberger

NO. OF
COPIES

- 2 U.S. Army Natick Laboratory
 Food Engineering Laboratory
 Natick, MA 01760
 A. Brynjolfssen
 R. Jarrett
- 1 Westinghouse Astronuclear Laboratory
 P. O. Box 10864
 Pittsburgh, PA 15236
 C. C. Silverstein

ONSITE

- 3 ERDA Richland Operations
 W. A. Burns
 W. C. Johnson
 H. E. Ransom
- 10 Rockwell Hanford Operations
 L. I. Brecke
 H. H. Hopkins
 R. E. Isaacson
 L. M. Knights
 C. W. Melody
 E. L. Moore
 J. D. Moore
 R. C. Roal
 H. P. Shaw
 D. D. Wodrich
- 28 Battelle-Northwest
 W. E. Anderson
 J. W. Bartlett
 C. L. Brown
 N. E. Carter
 H. T. Fullam
 J. H. Jarrett
 R. A. Libby (10)
 R. W. McKee
 R. E. Nightingale
 D. E. Olesen
 A. M. Platt
 W. E. Sande
 H. H. Van Tuyl
 Technical Information Files (5)
 Technical Publications