OCT 31 1961

C-23
75-OTS
Dep-

MASTER

ARF

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

ARF 1122-27

ISOTOPIC SOURCES OF SECONDARY RADIATION

by

I. Filosofo

Prepared for

The Office of Isotopes Development
United States Atomic Energy Commission

February 1, 1961

25 years of research

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of 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. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission to the extent that such employee or contractor prepares, handles or distributes, or provides access to, any information pursuant to his employment or contract with the Commission.

Printed in USA. Price \$2.50. Available from the Office of
Technical Services, Department of Commerce,
Washington 25, D. C.

ISOTOPIC SOURCES OF SECONDARY RADIATION

This work performed for

The Office of Isotopes Development
United States Atomic Energy Commission
Contract Number AT(11-1)-657

FINAL REPORT

by

ARMOUR RESEARCH FOUNDATION
of
Illinois Institute of Technology
Technology Center
Chicago 16, Illinois

Report written by
I. Filosofo

February 1, 1961

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

DISTRIBUTION LIST

No. of Copies

465

U. S. Atomic Energy Commission
Technical Information Service Extension
P. O. Box 62
Oak Ridge, Tennessee

35

U. S. Atomic Energy Commission
Office of Isotopes Development
Washington 25, D. C.

3

U. S. Atomic Energy Commission
Chicago Operations Office
Argonne, Illinois

1

ARF Main Files

1

ARF Report Library

1

"A" Files via Dir. of Phys. Res.

1

Nuclear Physics Section Files

This is the final report on ARF Project 1122 entitled, "Isotopic Sources of Secondary Radiation." This report covers the period from June 17, 1958 to October 17, 1960, and was conducted for the U. S. Atomic Energy Commission, Office of Isotopes Development, under Contract No. AT(11-1)-657.

Personnel who have contributed to this program include:
J. Ezop, I. Filosofo, T. Klippert, L. Reiffel, C. A. Stone, C. Vossler and L. Voyvodic.

Data concerning this project can be found in ARF logbooks C8393, C8394, C8399, C8548, C8956, C9485, C9621, C9624, C9625, C9632, and C9955.

Respectfully submitted,

ARMOUR RESEARCH FOUNDATION
of Illinois Institute of Technology

I. Filosofo,
Senior Physicist - Group Leader
Nuclear Physics Section

C. A. Stone, Supervisor
Nuclear Physics Section

APPROVED:

for L. Reiffel

Director of Physics Research

SUMMARY

A study has been made of the characteristics, design and use of beta excited x-ray sources. When energetic electrons interact with matter, both bremsstrahlung and characteristic x-rays are produced. The bremsstrahlung photons are distributed in a continuum while the characteristic radiations are monochromatic lines. However, due to x-ray self absorption in the target, the x-ray spectrum depends upon several parameters of the isotopic source design. For many applications, - critical absorptiometry, fluorescence excitation, radiography, etc., - best results are obtained by using a narrow band of x-rays of selected energy. Thus, our program was oriented toward a study of the parameters leading to an optimum x-ray output peaking at a specific energy.

An experimental program for measuring x-ray output and spectral distribution was carried out using three fission product beta emitters: promethium-147, krypton-85 and strontium-90-yttrium-90. Four geometrical source-target arrangements were studied: reflection, transmission, sandwich and mixture. Target materials ranged from copper to uranium with emphasis on tin (medium atomic number, Z) and lead (high atomic number, Z).

The yields of K x-rays from isotopic sources depend upon the atomic number of the target element, beta energy and geometrical factors of source-target configurations. A series of approximate formulae expressing the x-ray yield and optimum target thickness were constructed using existing theories of bremsstrahlung production and K-shell ionization.

Typical values of x-ray yields we observed are: a few percent of K photons per beta of strontium-90-yttrium-90, about one percent of K photons per beta of krypton-85 and a few tenths of one percent of K photons per beta of promethium-147. These values are in reasonable agreement with those calculated from the formulae.

Spectral distributions of x-rays from isotopic sources of optimum design exhibit, in general, a prominent peak in the energy region of the target's characteristic radiation. Best x-ray peak purity is obtained when a low energy beta emitter is used in combination with a medium Z target and a high energy beta emitter with a high Z target.

Results of study indicate the use of external targets with high energy beta emitters. For low energy beta emitters, higher output is obtained with source-target mixtures. Maximum obtainable outputs from typical sources of optimum design have been evaluated. The maximum x-ray flux per cm^2 of source area for a strontium-90 source and high Z sandwich target is about 10^6 K photons per cm^2 per sec at one foot. The self absorption of the betas in the beta source impose a limit on the x-ray output in this geometry. A similar limitation exists for the source-target mixtures due to self absorption of x-rays in the source. For a "pure" promethium-147 source in which the x-rays are produced in the isotope itself and in chemical carriers present, the maximum x-ray flux per cm^2 of source area is approximately 10^6 K photons per cm^2 per sec at one foot. A flux of 10^4 K photons per cm^2 per sec per curie of beta emitter at one foot can be obtained from a krypton-85 source and an efficient reflection geometry.

Two prototype sources for technical application have been designed and constructed. One uses 0.5 curies of krypton-85 contained in a thin walled nickel pipe for use with an external target. This source yields an x-ray spectrum peaking at the energy of the characteristic radiation of the chosen target material. The second source consists of 200 curies of "pure" promethium-147 in the form of a ceramic disk (0.7 cm diam) encapsulated in a brass cylinder with a thin stainless steel window. This source gives an x-ray spectrum peaking at 38 Kev, the characteristic K-radiation from promethium.

These sources have been demonstrated in several applications. Using the critical absorptiometry method, we have determined the silver content of photographic materials. Measurement of exposure doses on film badges and qualitative and quantitative analysis of medium and high Z materials were made by fluorescence excitation. The performance of isotopic sources in thickness measurements of metals and plastic materials was also investigated for gaging and production control applications. Radiography using the promethium-147 x-ray source was studied. These demonstrations are typical cases among a wide range of possible uses of x-rays where isotopic sources should have useful application.

In particular, problems requiring narrow and varied x-ray spectral distributions, our results clearly indicate the advantage of these sources as compared with the x-ray continuum of a conventional x-ray apparatus. The practical value of isotopic sources also lies in other unique features, such as high stability, long life, small physical size, no power supply and no continuous maintenance. These features of isotopic x-ray sources make them very attractive in permanent installations,

remote control devices and as portable units.

It is our belief that isotopic x-ray sources represent a valuable achievement in the field of radiation technology. These sources, by virtue of their characteristics and performance, should find widespread use in industrial and scientific applications.

TABLE OF CONTENTS

	<u>Page No.</u>
SUMMARY	v
LIST OF ILLUSTRATIONS	xi
LIST OF TABLES	xiv
I. INTRODUCTION	1
II. REQUIRED FEATURES OF ISOTOPIC X-RAY SOURCES	3
III. EXPERIMENTS AND RESULTS	5
A. Experimental Method	5
B. Strontium-90 Results	7
C. Krypton-85 Results	16
D. Promethium-147 Results	24
E. Promethium-147 with Mixed Targets	28
F. Results on Intensity of X-Rays	36
IV. ANALYTICAL STUDY OF X-RAY PRODUCTION	39
A. Relationship of Photon Yield Variations	39
B. Thick Target Photon Production by Beta Rays	43
C. Calculated K Peak Photon Intensities	53
D. Comparison with Experiments	56
V. APPLICATIONS OF EXPERIMENTAL AND ANALYTICAL RESULTS TO HIGH-LEVEL SOURCE DESIGNS	57
A. General Remarks	57
B. Strontium-90 Source Design	59
C. Krypton-Strontium Source Design	62
D. Promethium-147 Source Design	71

TABLE OF CONTENTS

(Continued)

	<u>Page No.</u>
VI. APPLICATIONS OF ISOTOPIC X-RAY SOURCES. . . .	78
A. Critical Absorptiometry.	78
B. Quantitative and Qualitative Analysis by Fluorescence Excitation	83
C. Thickness Gaging.	97
D. Radiography Using a Promethium-147 X-Ray Source.	99
REFERENCES	117

LIST OF ILLUSTRATIONS

<u>Fig. No.</u>		<u>Page No.</u>
1	Photon Energy Calibrations.	8
2	Resolution Curves for NaI Detectors.	9
3	Strontium-90 Source Assembly.	10
4	Experimental Layout for Transmission Target.	12
5	Spectra for Sr^{90} - Y^{90} and Tin in Transmission.	13
6	K-Peak Intensities for Sr^{90} - Y^{90} and Tin .	14
7	X-Ray Spectra from Sr^{90} - Y^{90} with Optimum Tin Targets in Different Geometries.	15
8	X-Ray Spectra from Sr^{90} - Y^{90} with Different Thicknesses of Lead in Transmission Geometry.	17
9	Spectra for Sr^{90} - Y^{90} and Lead In Reflection	18
10	K Peak Intensities for Sr^{90} - Y^{90} and Lead in Transmission.	19
11	K Peak Intensities for Sr^{90} - Y^{90} and Lead in Reflection.	20
12	Spectra for Kr^{85} and Tin in Transmission. .	21
13	Spectra for Kr^{85} and Lead in Transmission	22
14	K Peak Intensities for Kr^{85} with Tin and Lead.	23
15	X-Ray from Two Pm^{147} Sources with Lucite	25
16	X-Ray Spectra from Pm^{147} and Tin Target	26
17	K Peak Intensities for Pm^{147} and Tin. . . .	27
18	Spectra from Pm^{147} with Tin, Lead and Uranium (90°).	29

LIST OF ILLUSTRATIONS

(Continued)

<u>Fig. No.</u>		<u>Page No.</u>
19	Spectra for Pm ¹⁴⁷ and Samarium Mixture . . .	31
20	K Peak Intensities for Promethium-147 Mixed with Samarium Oxide. Sources have Different Thicknesses and the Same Total Activity. . . .	33
21	X-Ray Spectra from Different Thicknesses of Pm ¹⁴⁷ - Sm ₂ O ₃ Mixture.	35
22	X-Ray Spectra from Pm ¹⁴⁷ Source-Target Mixtures.	37
23	Calculated "K Photons" Produced by Beta Excitation in Tin and Lead Targets.	47
24	Theoretical K Shell Cross Sections σ_K , and Residual Range R, for Monoenergetic Electrons	50
25	X-Ray Spectra for Sr ⁹⁰ -Uranium Target Sandwich and Kr ⁸⁵ with Lead Cone Target.	63
26	Kr ⁸⁵ X-Ray Source Arrangements	66
27	Krypton-85 Source Assembly	67
28	X-Ray Spectra from Kr ⁸⁵ with Different Cone Targets.	68
29	Scintillation Counter Spectra for Kr ⁸⁵ with Sn and Pb Pipe Targets	70
30	Promethium-147 Source Assembly	74
31	X-Ray Spectrum from 200 Curie Pm ₂ O ₃ Source	76
32	Antimony K X-Ray Attenuation in Photographic Material.	81
33	Experimental Arrangement for Silver Fluorescence X-Ray Analysis	84
34	K X-Ray Fluorescence of Photographic Films of Different Silver Thickness	86

LIST OF ILLUSTRATIONS

(Continued)

<u>Fig. No.</u>		<u>Page No.</u>
35	Silver Fluorescence Intensities of Photographic Films.	88
36	Silver Fluorescence Intensity Vs X-Ray Dose in Film Dosimeters	92
37	Silver Fluorescence Intensity Vs Gamma-Ray Dose in Film Dosimeter.	93
38	L X-Ray Fluorescent Spectra of Lead Dust on Filter Paper	95
39	X-Ray Fluorescent Spectra of Mercuric Iodide on Filter Paper.	96
40	Relative X-Ray Transmission Through Lucite Using a NaI Detector.	100
41	Relative X-Ray Transmission Through Aluminum Using a NaI Detector	101
42	Relative X-Ray Transmission Through Steel Using a NaI Detector.	102
43	Relative X-Ray Transmission Through Aluminum Using an Ionization Chamber.	103
44	Relative X-Ray Transmission Through Steel Using an Ionization Chamber	104
45	X-Ray Attenuation in Steel.	105
46	Radiographs Using Pm ¹⁴⁷ A - 45 Minute Exposure, Collimated B - 4.5 Minute Exposure, Uncollimated	106
47	Radiography Apparatus	107
48	Comparative Radiographs A - Pm ¹⁴⁷ B - Conventional X-Ray Machine	111
49	Radiograph Using Pm ¹⁴⁷ Polaroid 3000 Film. .	115
50	Radiograph Using Pm ¹⁴⁷ Polaroid 3000 Film. .	116

LIST OF TABLES

<u>Table No.</u>		<u>Page No.</u>
I	Experimental K Photon Yields.	38
II	Photon Yield Function for Beta Excited X-Ray Sources.	41
III	Calculated Optimum Thicknesses of Slab Targets for Tin and Lead K Photon Peaks.	42
IV	Experimental and Calculated Optimum Thicknesses for Transmission Geometry.	44
V	$\omega_K(Z)$ - K Fluorescence Yield Vs Atomic Number.	49
VI	Calculated Beta Excited Photon Production. . .	54
VII	Expected Performance of Sandwich Sources . .	55
VIII	Intensities of Silver Fluorescence Radiation from Developed Film Dosimeters.	90
IX	Optimum Thicknesses of Absorbers for Maximum Sensitivity Using 40 Kev X-Ray.	110

ISOTOPIC SOURCES OF SECONDARY RADIATION

I. INTRODUCTION

X-rays in the energy range from a few Kev to 100 Kev play an important role in the growing use of radiation in research and technology. Their principal areas of application are mass density and thickness gaging, industrial and medical radiography as well as composition analysis by absorptiometry and fluorescent excitation techniques. The need for electromagnetic radiation in the mentioned energy range are currently covered by conventional x-ray machines. Low energy gamma rays represent an alternative possibility and indeed they have proved to be satisfactory sources in some particular applications. Very few long lived isotopes, however, emit low energy gammas and because of their complex decay schemes they are of limited use where a narrow photon energy distribution is desirable.

It was proposed^{1, 2} that x-ray sources can be obtained by using β -emitting radioisotopes. High energy betas brought to rest in a target lose their energy by radiative and ionization processes. Most of the energy is dissipated in outer shell ionization of the stopping medium. However, a substantial fraction of the electron's energy goes into the production of bremsstrahlung x-rays and characteristic x-rays following inner shell ionization. The energy distribution and the flux of x-rays depend mainly upon the nature of the target, the electron energies and the strength of the beta source.

Particularly attractive is the possibility of assembling compact and portable x-ray sources which do not require any power supply. In addition, especially if long-lived beta emitters are used, these sources can be

an ideal solution in many applications requiring a high stability x-ray flux. Comparison between specific activity of beta emitters and electron currents used in x-ray tubes suggests that x-ray output of isotopic sources can hardly compete with that of conventional x-ray machines. However, the unique features anticipated above should make the isotopic x-ray sources very attractive and advantageous substitutes for conventional sources in many scientific and technical applications.

A considerable amount of work has already been done in this laboratory and elsewhere³⁻⁷ for the understanding of the physical processes involved in the x-ray production and for the development of isotopic sources of some utility. Not much effort has been dedicated, however, to the design study of high level x-ray sources and to a systematic analysis of the dependence of x-ray output efficiency on the physical and geometrical parameters of source configuration.

This report describes our recent work on isotopic x-ray sources. The program is oriented towards the goal of optimizing the design of high level isotopic sources and investigating their capability and performance in typical scientific and technical uses.

The aim of this project first suggested an extensive experimental and analytical study of the physics involved in the x-ray production by beta rays. A systematic program of measurements of x-ray output has been carried out using different beta emitters and a variety of target materials and geometrical configurations. Because of their large scale availability, low cost and long half lives, our work has been oriented to the use of the fission product beta emitters promethium-147, krypton-85

and strontium-90 - yttrium-90.

The analysis of the experimental results leads to an approximate mathematical formulation of x-ray output as a function of beta energy, target material and source configuration. This correlation provides a quantitative interpretation of the experimental results and also gives the basic information necessary for an optimum design of a source of specific performance characteristics. Prototype high level sources designed according to our experimental and analytical study have been constructed, and their potentiality and performance demonstrated in a few selected applications.

II. REQUIRED FEATURES OF ISOTOPIC X-RAY SOURCES

It is well known that x-rays produced in the interaction of energetic electrons with matter include both bremsstrahlung x-rays and characteristic x-rays following inner shell ionization. Characteristic radiation is composed of monochromatic lines of energies determined by the electronic transitions following the ionization. The bremsstrahlung radiation is instead distributed in a "continuum" extending up to the maximum beta energy. For a thick target, mainly due to self-absorption and fluorescent radiation, a more complicated picture is necessary to account for the observed spectrum of x-ray output. Experimental data has shown, however, that x-ray spectra from thick targets is still reminiscent of the spectral distribution from very thin targets and appears as a superimposition of monoenergetic "lines" and of a continuum.

It is also known that the x-ray spectral distribution can vary to a certain extent with target nature and geometrical configuration and can approach either a broad distribution or a spectrum peaking strongly

at the K-radiation of the target material. Then, in undertaking a study aiming at the design of isotopic sources for practical uses, one may follow one of two alternative orientations: one can study and develop sources giving a broad distribution of x-ray energies or investigate and define the conditions for the highest purity of an x-ray peak of specific energy.

For gaging and radiography, the main requirements of x-ray sources may be estimated in terms of the change in detector signal, ΔI , which arises from a fractional change $\Delta\rho/\rho$, where ρ is thickness x density of the absorber. This measure of sensitivity can be expressed, for exponential attenuation of monochromatic x-rays, as

$$\text{Sensitivity} = \Delta I / (\Delta\rho/\rho) = -\mu I_0 e^{-\mu\rho} \rho. \quad (1)$$

To increase sensitivity, the unattenuated signal I_0 should be made large. This suggests the use of high source intensity, small source to detector distance and/or high detector efficiency. By differentiating (1), maximum sensitivity is expected under these conditions when the photon energy is chosen which has absorption coefficient $\mu = 1/\rho$. By taking into account statistical variation of the signal at a certain sensitivity, one can actually conclude that a measurement will be more readable⁸ when x-rays have an absorption coefficient which satisfies the relationship $\mu = 2/\rho$.

Irrespective of statistical factor, the importance of which depends on time response of the detecting system, there exists an optimum x-ray energy for each mass thickness inspection or control. These conditions are difficult to achieve and in most of the current usage broad spectral distributions are employed. In general, however, improvement would be expected if a monochromatic beam of x-rays can be used.

The requirement of "line" spectra of x-ray is particularly imperative in the mass thickness measurement by critical absorptiometry. This method of gaging implies the use of monochromatic beams of x-ray of energy just above the absorption edge of an inner shell of the material (usually the K-shell). The degree to which one can achieve the high sensitivity inherent to this method depends very strongly on the purity of an x-ray "line".

X-ray broad distribution can be tolerated in the method of inspection or analysis using fluorescence excitation. Investigations of this technique indicate, however, that limited spectral distribution leads to a smaller background and to better resolution. Based on the approximate analysis above, the choice of desired x-ray spectrum would be monochromatic radiation of energy determined by the specific material and type of testing.

Thus, our program on isotopic x-ray sources has been oriented toward the study of methods and evaluation of physical and geometrical parameters leading to an optimum x-ray output peaking at a specific energy.

III. EXPERIMENTS AND RESULTS

A. Experimental Method

Our study on isotopic x-ray sources has been particularly concerned with the importance of the parameters determining the observed x-ray intensity and spectral distribution. More specifically, we have used the three beta emitters, promethium-147, krypton-85 and strontium-90, to investigate the x-ray output features as a function of target atomic number, target thickness and beta source-target configuration.

Although some of the experiments have been done using a variety of target materials ranging from copper to uranium, most of our systematic study has been carried out using one medium Z and one high Z target element: namely, tin and lead. The results of these two elements with the wide range of beta energies covered by the three mentioned isotopes give a good picture of the potentialities of this method of x-ray production.

In observing x-rays from beta sources and external targets, the following four geometrical arrangements were used in different experiments:

- (1) transmission, where the target material is placed between the source and the x-ray detector;
- (2) reflection, where the beta source is between the target and detector;
- (3) sandwich, with target material on both sides of the beta source, and
- (4) 90° geometry, similar to that used in x-ray machines, where the x-rays are detected at 90° to the beta particle direction, the target being at 45° to both.

The x-ray intensity and spectral distribution were studied using scintillation spectrometers in connection with a 256 channel pulse height analyzer. The x-ray spectra reported in the following paragraphs are as originally recorded by the detection system. No attempt has been made for an evaluation of the real spectra by the unfolding of the observed x-ray distributions. In all the measurements the detectors have been shielded, and the x-rays detected through a lead collimator lined with cadmium and copper layers to eliminate high energy fluorescent x-rays

from the shield. Thick (1 inch) and thin (1/8 inch) NaI(Tl) crystals 1-1/2 inches in diameter were used, coupled to two inch diameter phototubes. Figure 1 shows the linearity of energy calibration for the spectrometer. Sources used for the calibration were cesium-137, cadmium-109, mercury-203 and europium-155, using both the gamma rays and the characteristic x-rays of daughter nuclei. (Peak positions for our K and L characteristic x-rays showed very good agreement with the calibration curves.) Figure 2 shows the resolution (full width at half maximum as percent of energy for the peak intensity) as function of photon energy. As derived from the observed calibration "lines", the resolution is seen to be linear with $1/E^{1/2}$, and the 25 Kev tin and 75 Kev lead characteristic x-rays should appear with widths of 7.5 and 15 Kev, corresponding to resolutions of 30 and 20 percent respectively.

B. Strontium-90 Results

The strontium-90 beta source was prepared by the Nuclear Chicago Corporation, and consists of 10 ± 1 mc of strontium fused with a glass matrix between two mica windows and held in a steel retainer ring.

Figure 3 shows the beta source configuration and its physical dimensions. Restrictions imposed by safety rules lead to a source of about 400 mg/cm^2 in thickness, inclusive of the two mica windows (about 10 mg each). As is known from experiments, the half-thickness of a beta spectrum attenuation is about one-tenth of the maximum beta range. Hence, with the mentioned source thickness, only a few percent of strontium-90 betas (0.6 Mev) can be utilized on external targets, and the source has been considered as an yttrium-90 source (2.2 Mev) in all the phases of this work.

FIG.1- PHOTON ENERGY CALIBRATIONS

FIG.2-RESOLUTION CURVES FOR NaI DETECTORS

FIG.3- STRONTIUM-90 SOURCE ASSEMBLY

Measurements of the x-ray output for all geometries except for 90° reflection were made with the target in contact with the beta source assembly. In Fig. 4 a typical experimental layout for a transmission target experiment is represented.

The 90° geometry has been studied with the beta source at about two inches from the center of the target and the two components were held together by a styrene foam frame.

A beta stopper of lucite was inserted between the source and the detector in all those measurements where the target thickness was not enough to stop all the betas.

Our main observations for tin targets are shown in Figs. 5, 6 and 7. Spectral distribution of x-rays are readily seen to be in qualitative agreement with the scheme of x-ray production anticipated. In Fig. 7 the bremsstrahlung contribution and its self-absorption above the K absorption edge of the target is particularly evident; the spectrum for 90° geometry also indicates that the bremsstrahlung contribution at large angles to the beta particle direction is reduced as expected from theory. Irrespective of the geometrical arrangement, the x-ray spectra exhibit a clean peak centered at 25 Kev, the energy of the characteristic K radiation of the target material. It is believed that bremsstrahlung peaking by self-absorption and lines of characteristic radiation (K_α and K_β) determine the observed K peak. Detectors of much higher energy resolution should be used for a detailed analysis of this feature, which is not, however, essential to the scope of this work. As seen in Fig. 7, the amplitude of the K peak depends on target thickness and geometrical configuration; for transmission

FIG. 4 - EXPERIMENTAL LAYOUT FOR TRANSMISSION TARGET

FIG.5- SPECTRA FOR $Sr^{90}-Y^{90}$ AND
TIN IN TRANSMISSION

FIG.6- K PEAK INTENSITIES FOR $\text{Sr}^{90} - \gamma^{90}$ AND TIN

FIG. 7- X-RAY SPECTRA FROM $\text{Sr}^{90}\text{-Y}^{90}$ WITH OPTIMUM TIN TARGETS IN DIFFERENT GEOMETRIES.

and sandwich target the peak amplitude reaches a maximum value for an optimum target thickness.

Figures 8, 9, 10 and 11 summarize the more significant results with lead targets. Here the spectra are peaking at the K x-ray of lead, and, especially in the transmission geometry, one has evidence of the contribution of the continuum to the peak from the narrowing of the spectrum at increasing target thickness. At 270 mg/cm^2 , which corresponds to the optimum thickness, the observed peak shows a width at half height of about 40 percent while at thicknesses of the order of maximum beta range the peak exhibits a shape very similar to that expected for the detector energy resolution.

C. Krypton-85 Results

As prepared by the Nuclear Chicago Corporation, the krypton-85 source was a flat disk 3 inches in diameter and 1/4 inch deep, containing approximately 75 mc. The exit window for beta particles was very thin, ~ 0.002 inch mica, while the source backing was 1/16 inch stainless steel. With this single window beta source only transmission and 90° reflection experiments were possible. Our results with tin and lead targets are shown in Figs. 12, 13 and 14. The spectra are seen to be quite similar to those with strontium-90 source with, however, different values for optimum target thicknesses and x-ray production efficiency. This similarity suggested that a complete study inclusive of sandwich geometry using a more sophisticated source was not worthwhile to pursue. We are confident, however, that our data on this gaseous isotope, combined with that obtained with strontium-90, should offer an adequate orientation for the design of an x-ray source using krypton-85.

FIG. 8- X-RAY SPECTRA FROM $Sr^{90}-Y^{90}$ WITH DIFFERENT THICKNESSES OF LEAD IN TRANSMISSION GEOMETRY.

FIG.9- SPECTRA FOR $\text{Sr}^{90}-\text{Y}^{90}$ AND LEAD IN REFLECTION

FIG.10 - K PEAK INTENSITIES FOR $\text{Sr}^{90}\text{-Y}^{90}$ AND LEAD IN TRANSMISSION

FIG.II- K PEAK INTENSITIES FOR $\text{Sr}^{90}\text{-Y}^{90}$ AND LEAD IN REFLECTION

FIG.12- SPECTRA FOR Kr⁸⁵ AND TIN IN TRANSMISSION

FIG.13- SPECTRA FOR KR⁸⁵ AND LEAD
IN TRANSMISSION

FIG.14- K PEAK INTENSITIES FOR Kr^{85} WITH TIN AND LEAD

D. Promethium-147 Results

Since promethium-147 beta particles have short range, it was necessary to produce a thin source with thin windows in order to make efficient use of the betas and also to reduce the x-ray production in the source assembly. Most of the data reported in this section were obtained with a promethium-147 beta source of about 7.5 mc in an assembly similar to that sketched in Fig. 3 except that much thinner windows were used and the holding ring was made out of lucite. The source has been prepared by evaporating a promethium chloride solution on thin mica ($\sim 2 \text{ mg/cm}^2$) and then covering with similar mica backing window. Sealing was accomplished with Duco and epoxy cements. This source showed the x-ray spectrum (source A) illustrated in Fig. 15 when covered by a lucite beta stopper. The bremsstrahlung spectrum appears to peak at $\sim 20 \text{ Kev}$ due to self-absorption, and has superimposed photon peaks at about 40 and 85 Kev as well as lower intensity lines which were followed out to 1.3 Mev. These photons are ascribed to the presence of europium-155 and promethium-148 gamma emitters in the fission product source. For comparison, the spectrum from a commercial promethium-147 beta source is also shown in Fig. 15. While the latter is relatively free of gamma contamination, there is a broad bremsstrahlung region and appearance of the lead L line, due to the use of a soft lead glass matrix.

The observed production of x-rays with external tin targets and source A is shown in Figs. 16 and 17. With transmission and with sandwich geometry the maximum yield at the 25 Kev peak is seen to occur for very thin targets, about one-third the thickness required to stop the β particles completely.

FIG.15- X-RAYS FROM TWO Pm^{147} SOURCES WITH LUCITE

FIG. 16- X-RAY SPECTRA FROM Pm^{147} & TIN TARGET.

FIG.17- K PEAK INTENSITIES FOR Pm^{147} AND TIN

Figure 18 brings out most clearly the x-ray production from promethium-147 for the region 10 Kev to 100 Kev and high Z targets.

Using the 90° geometry, x-rays from the source itself and gamma contamination are removed.

Our measurements indicate that the yields of K x-rays for promethium-147 betas are, in general, much lower than those measured for strontium-90 and krypton-85 and are particularly low for high Z targets.

With the commercially available promethium-147 source mentioned above, we experienced K x-ray yields even lower than those observed with our experimental thin source. This was not surprising, however, since the source fabrication was similar to that described for strontium-90, beta source and window thicknesses greatly reduced the energy and flux of betas.

It is very likely that any safe encapsulation of promethium-147 or any other low energy beta emitter will drastically reduce the output of an x-ray source assembly using external targets. The limitation on the use of this geometry is particularly evident if a high level x-ray source is desired which implies a large amount of beta emitter. In this case, unless a large area source is designed, most of the beta energy will be dissipated in the source itself and in its container rather than in an external target.

E. Promethium-147 with Mixed Targets

The above consideration led us to believe that the best utilization of short range betas for the design of compact x-ray sources would be the intimate mixture of the beta emitter with a target material.

FIG.18- SPECTRA FOR Pm^{147} WITH TIN, LEAD, AND URANIUM (90°)

The production of characteristic x-rays with source-target mixtures of promethium-147 have previously been studied by Brownell et. al.⁹ using molybdate and tungstate mixtures.

Our study of this type of source has been directed toward a particular case which should represent the best solution for high level x-ray sources. It seemed to be obvious that maximum x-ray output from internal target sources should be given by a source in which the beta emitter is not diluted in a target compound and the x-ray target is represented by the isotope itself and possible carriers.

We considered the promethium-147 oxide a convenient chemical form of the isotope for this type of source; thus we performed our study of x-ray spectra and yields on a simulation material composed of samarium ($Z = 62$) in the oxide form mixed with a convenient amount of promethium-147 ($Z = 61$).

A set of three sources were prepared in identical containers made out of 1/2 inch lucite blocks in each of which a 1/4 inch diameter hole was drilled, leaving a 1/32 inch thick flat bottom. Powdered samarium oxide was deposited in the holes so as to obtain thicknesses equivalent to one, two and three times the maximum beta range, and in each hole, 100 μc of promethium chloride solution was added and thoroughly mixed with the samarium oxide. After drying, the sources were sealed with tightly fitting 1/4 inch lucite rods cemented into the lucite blocks.

Figure 19 shows the x-ray spectrum observed with the 100 mg/cm² source. For comparison, the spectrum given by a "blank source" prepared by drying 100 μc of promethium-147 solution in a lucite container identical to those of the mixed sources is also shown.

FIG.19-SPECTRA FOR Pm^{147} AND SAMARIUM MIXTURE

The three samarium sources showed almost identical x-ray spectrum peaking at about 40 Kev, the energy of K characteristic x-rays of samarium. The relative counting rate for x-rays of energy from 30 to 50 Kev are plotted in Fig. 20, where the value for zero source thickness corresponds to the bremsstrahlung x-rays produced by the "blank source" in its lucite container. The yield of K x-rays per beta particle changes very slowly with source thickness and seems to reach a maximum value for an optimum thickness equivalent or even smaller than the maximum beta range.

The optimum source thickness mentioned above corresponds to the most intense K x-ray peak that can be obtained with a given amount of beta emitter; in other words, it defines the conditions for the most economical utilization of a beta emitter in a source-target mixture when no restrictions are imposed to the area of the isotopic x-ray source.

There are, however, some applications which require small size and, at the same time, high level x-ray sources. As an example, in radiography a strong limitation in source size is imposed by the desired resolution while higher x-ray output is preferred for a reduced exposure time. Thus, in studying this type of isotopic x-ray source we have been interested not only in the solution which corresponds to the maximum x-ray yield per beta particle but also in that which insures the maximum x-ray output per unit of source area. The results summarized in Fig. 20 indicate that optimum source thickness does not correspond to the maximum obtainable output from a source of a given area. If the K x-ray counting rates reported there were normalized to constant activity per unit of volume, the greater x-ray output will be given by the 150 mg/cm^2 source. However, one "curie" of those x-rays will be more expensive than a curie

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

FIG.20- K PEAK INTENSITIES FOR PROMITHIUM-147 MIXED WITH SAMARIUM OXIDE. SOURCES HAVE DIFFERENT THICKNESS AND THE SAME TOTAL ACTIVITY

produced by a source of optimum thickness.

A detailed investigation of this problem was carried out by using a set of five sources of constant activity per unit of volume (6 mc/g) and different thicknesses. The sources were encapsulated in lucite containers identical to those described above. Since a promethium-147 solution of unknown gamma contamination was used, a "blank source" was also prepared.

Spectral distribution of x-rays emitted by some of these sources are shown in Fig. 21. The spectrum of the "blank source" showed that the beta emitter was quite free of promethium-148 and other gamma emitters. This accounts for the cleaner x-ray spectrum of these sources as compared with that in Fig. 19.

A significant feature of this type of isotopic source must be noticed, i.e., the saturation of the K peak amplitude at increasing source thickness. For all practical purposes, the output of the 659 mg/cm² source in Fig. 21 represents saturation; greater source thickness will produce the same general features of the x-ray spectral distributions and will not increase the K peak amplitude by more than a few percent.

The x-ray output, for the maximum available specific activity of promethium-147 material and source thickness corresponding to saturation yield, should represent the maximum obtainable per unit of area of an isotopic x-ray source using promethium-147. Peak energy of x-ray spectra from "pure" beta emitters is determined, of course, by the atomic number of the isotope itself and this may be a drawback of this type of source when compared with the flexibility of the external target geometry.

FIG.21- X-RAY SPECTRA FROM DIFFERENT THICKNESSES OF Pm^{147} — Sm_2O_3 MIXTURE.

Spectral distributions peaking at an energy other than that characteristic of the beta emitter can be obtained, however, by mixing the isotope with a convenient target, but the x-ray output will depend on the concentration of the beta emitter in the mixture. Such type of source was investigated by using mixtures of promethium-147 with antimony oxide and tungsten oxide. Two sources of thickness sufficient to insure x-ray saturation yields were prepared in lucite containers. The x-ray spectra obtained with these sources are shown in Fig. 22, together with that simulating the "pure" beta emitter. The three spectra are normalized to the same peak amplitude; K x-rays of iodine escaping the detector account for the smaller peaks on the low energy side of samarium and tungsten x-ray spectra.

F. Results on Intensity of X-Rays

From the source strength, geometry and observed counting rate with each of the sources, the percent K x-ray yield per beta particle striking the target has been estimated.

Values of maximum yield for transmission geometry as listed in Table I are in approximate agreement with previous work as reviewed by Starfelt et. al.¹⁰ One area of discrepancy is that they report higher yields for the lead K peak with high energy beta emitters. This discrepancy may be accounted for by the non-ideal condition in which our measurements have been performed. As mentioned above, our strontium-90 source has a non-negligible thickness. Thus the results of our measurements cannot be compared directly with data obtained with an ideal thin source and closer source-target configuration.

Table I also gives the maximum yield for the simulated pure promethium-147 source. There is a range of thicknesses for which its

FIG. 22- X-RAY SPECTRA FROM Pm^{147} SOURCE — TARGET MIXTURES.

TABLE I
EXPERIMENTAL K PHOTON YIELDS

Source	$E_{\max}$ Mev	$T_{1/2}$ yrs.	R_{β} mg/cm ²	Target	t_{opt} mg/cm ²	K peak photons percent/ β particle
Pm^{147}	0.226	2.6	50	Sn	18	0.3
				Sm_2O_3	(25-50)	0.2
				Pb	30	<0.1
Kr^{85}	0.67	10.3	250	Sn	54	0.7
				Pb	100	1.0
Y^{90}	2.20	27.7	1100	Sn	110	2.2
				Pb	250	3.3

K peak energy ranges (Kev): Sn (17.5 - 32.5); Sm (30 - 50); Pb (60 - 90)

$1/\mu_K$ (mg/cm²): Sn (110); Sm (180); Pb (660)

Values of t_{opt} are for transmission geometry, except for Sm_2O_3 source-target mixture.

K peak yields are derived per beta particle striking the target, from sandwich, transmission and mixed source-target geometries.

value is practically constant.

IV. ANALYTICAL STUDY OF X-RAY PRODUCTION

A. Relationship for Photon Yield Variations

In order to improve the quantitative interpretation of the x-ray spectra observed with experimental sources, and to aid in the design of new sources with specific performance characteristics, an approximate mathematical formulation has been developed. The primary intent here was to cover a wide range of beta energies, target geometries and source geometries, rather than concentrating on more exact solutions for particular cases.

A simple formulation of the observed x-ray yield per beta particle as a function of the above mentioned parameters can be attempted by assuming an isotropic distribution of x-rays at the production by beta excitation and by referring the x-ray propagation and yield to a limited solid angle in a direction normal to external slab targets.

Viewing the x-ray yield as governed by the two processes, production by beta excitation and self-absorption in the target, the yield $Y(W, t)$ of photons of energy W per beta particle striking a target of thickness t has been approximated by the expression

$$Y(W, t) \sim N(W) \int_0^t A_{\beta}(W, t) A_x(W, t) dt \text{ photons}/\beta \quad (2)$$

where $A_{\beta}(W, t)$ and $A_x(W, t)$ represent the absorption function for betas and x-rays and $N(W)$ is the thick target asymptotic function of x-ray production by betas.

A similar expression of x-ray yield can be formulated for the source-target mixture when the integration is extended also to the uniform distribution of the beta source into the target itself. However, for low energy beta emitters, for which this geometry is particularly attractive, the fraction of betas escaping the source is negligible at source thicknesses much less than the K x-rays relaxation length, and therefore, the yield can be approximated by

$$Y(W, t) = \frac{N(W)}{t} \int_0^t A_x(W, t) dt \text{ photons}/\beta. \quad (3)$$

The absorption of betas in the target can be represented by an exponential law.¹¹ For the beta absorption coefficient we used the relation $\mu_\beta = 8/R_{\max}$ which reflects the experimental evidence of a beta half thickness of about one-tenth of the maximum range. The equations expressing the variation of photon yield on this basis are listed in Table II for the principal source-target configurations used in practice.

For the transmission and sandwich target whose yield functions go through maxima, differentiation of expressions 4) and 7) give the relations for optimum target thicknesses. For the mixed sources, the simplifying assumption used in deriving the yield function, led to the expression (9) that represents the x-ray yield for source thicknesses equivalent or greater than the maximum range. As discussed above, optimum source thickness is not critical and is also of the order of maximum beta range. Thus the maximum yield can be evaluated by (9) for $t = R_{\max}$.

Table III shows the calculated values of optimum target thicknesses over a range of beta emitting isotopes. From a comparison of these calculated values with those indicated in Figs. 5 to 18 and the transmission

TABLE II
PHOTON YIELD FUNCTIONS FOR BETA EXCITED X-RAY SOURCES

Transmission Geometry

$$Y_T(W, t) = N(W) \frac{\mu_\beta}{\mu_\beta - \mu_x} (e^{-\mu_x t} - e^{-\mu_\beta t}) \text{ photons}/\beta \quad (4)$$

$$t_{\text{opt}} = \frac{\lg \mu_x - \lg \mu_\beta}{\mu_x - \mu_\beta} \quad (5)$$

Reflection Geometry

$$Y_R(W, t) = N(W) \frac{\mu_\beta}{\mu_\beta + \mu_x} \left[1 - e^{-(\mu_\beta + \mu_x)t} \right] \text{ photons}/\beta \quad (6)$$

Sandwich Geometry (Back Target, $t \geq R_{\text{max}}$)

$$Y_S(W, t) = \frac{N(W)}{2} \left[\frac{\mu_\beta}{\mu_\beta - \mu_x} (e^{-\mu_x t} - e^{-\mu_\beta t}) + \frac{\mu_\beta}{\mu_\beta + \mu_x} e^{-\mu_x t} \right] \text{ photons}/\beta \quad (7)$$

$$t_{\text{opt}} = \frac{\lg (\mu_\beta + \mu_x) - \lg 2\mu_x}{\mu_\beta - \mu_x} \quad (8)$$

Source-Target Mixture (Low Energy Beta Emitters)

$$Y_M(W, t) = N(W) \frac{(1 - e^{-\mu_x t})}{\mu_x t} \text{ photons}/\beta \quad (t \geq R_{\text{max}}) \quad (9)$$

TABLE III

CALCULATED OPTIMUM THICKNESSES OF SLAB TARGETS FOR
TIN AND LEAD K PHOTON PEAKS

Beta Source	Pm ¹⁴⁷	Kr ⁸⁵	Y ⁹⁰
E _{max} - Mev	0.226	0.67	2.2
R _β - mg/cm ²	50	250	1100
Sn (1/μ _K = 110 mg/cm ²)			
Sandwich t _{opt} - mg/cm ²	15	36	58
Transmission t _{opt} - mg/cm ²	18	55	124
Pb (1/μ _K = 660 mg/cm ²)			
Sandwich t _{opt} - mg/cm ²	25	79	185
Transmission t _{opt} - mg/cm ²	31	100	272

optimum thicknesses listed in Table I, we find that the agreement is surprisingly good. Table IV compares these values. From rough plots of the yield variations (relations (4), (6), (7) and (9)) we have also found that the shapes of the calculated curves agree quite well with the experimental variations in our previous study. The lower t_{opt} values at which maximum K yield is reached in sandwich geometry are also in good agreement with experiments. Some discrepancies between calculated and experimental value of optimum target thickness in sandwich geometry are expected when the beta source has a considerable thickness. The experimental value of optimum thickness for yttrium-90 source and tin target in sandwich geometry as seen in Fig. 6 is larger than the calculated one in Table III. However, the K x-rays of tin produced in the back target are attenuated in passing through the relatively thick beta source assembly. Thus the experimental optimum target thickness should be intermediate between that of an ideal sandwich source and that of a transmission geometry.

B. Thick Target Photon Production by Beta Rays

To obtain absolute values of photon yields $Y(W, t)$ for the source-target configurations of interest in Table I, it is now necessary to evaluate the thick target saturation function $N(W)$.

As discussed above, the two principal mechanisms giving rise to x-rays in a target material by beta bombardment are: (a) bremsstrahlung which gives a continuum spectrum of photons with energies up to $W = E_{\text{max}}$, and (b) characteristic x-rays due to ionization of inner electronic shells.¹² Then, the production function for photons in the region of the K peak directly produced by beta particles can be represented by

TABLE IV

EXPERIMENTAL AND CALCULATED OPTIMUM THICKNESSES
FOR TRANSMISSION GEOMETRY

	Tin Target		Lead Target	
	Exp. t_{opt}	Calc. t_{opt}	Exp. t_{opt}	Calc. t_{opt}
Pm ¹⁴⁷	18	18	30	31
Kr ⁸⁵	54	55	100	100
Y ⁹⁰	110	124	250	272

$$N(W_K) = N_{bp} + N_{ks} \text{ photons}/\beta \quad (10)$$

where $N_{bp} = N_b(W_1, W_2)$ is the bremsstrahlung component between photon energies W_1 and W_2 which produces the "bremsstrahlung peaking" in the K x-rays region, and N_{ks} is the number of characteristic x-rays due to K shell ionization.

A substantial contribution to the K x-ray yield is also given by the fluorescent radiation following photoelectric absorption of the high energy bremsstrahlung in the target. It is expected that this fluorescent radiation is produced through the target with a distribution somehow different from that of the photon components directly produced by betas and for which the equation (2) applies. However, in a first approximation and within limits which will be discussed later, the production function of photons in the K region should include the fluorescent component N_{fl} . Then equation (10) becomes:

$$N(W_K) = N_{bp} + N_{ks} + N_{fl} \text{ photons}/\beta \quad (11)$$

Absolute values of the mentioned components of the K x-rays production function $N(W)$ were evaluated by graphical integration as well as by analytical methods.

1. The Bremsstrahlung Components

To find absolute values, $N_b(W)$, we have normalized the differential spectra by graphical integration, using the bremsstrahlung spectrum for phosphorus-32 as calculated by Evans,¹¹ together with his expression for the absolute flux of energy radiated, i.e.,

$$I_T = k \left(\frac{E_{rms}}{E_{max}} \right)^2 Z E_{max}^2 \text{ Mev} \quad (12)$$

(We have taken the value $k = 7 \times 10^{-4} \text{ Mev}^{-1}$ as suggested by Evans.¹¹)

The curved marked N_{bp} in Fig. 23 shows the results obtained by applying this graphical procedure to promethium-147, krypton-85 and yttrium-90 normalized beta spectra. The same curve approximately fits both tin and lead targets for the energy intervals W_1 to W_2 taken from Table I, i. e., 17.5 to 32.5 Kev for tin and 60 to 90 Kev for lead.

In addition to the graphical integration procedure used above, a study was made of bremsstrahlung intensity when expressed in analytical form. Examination of the phosphorus-32 bremsstrahlung intensity spectrum derived by Evans¹¹ indicates that for beta sources the flux $I(W) = N(W) W$ decreases nearly linearly with W , quite similar to the linear variation for monoenergetic electrons.

Assuming then a linear flux spectrum $I(W) = C (E_{max} - W)$, integrating over the allowed photon energy region and equating the results with I_T as given by relation (12), we find for the differential photon spectrum due to beta excitation

$$N_b(W)dW = 2k \left(\frac{E_{rms}}{E_{max}} \right)^2 Z \left(\frac{E_{max}}{W} - 1 \right) dW \text{ photons}/\beta \quad (13)$$

when E_{max} , W and dW are all expressed in Mev.

The analytical form (13) for the differential spectrum also allows a convenient derivation of the number of photons with energies greater than W , i. e.,

FIG.23 - CALCULATED "K PHOTONS" PRODUCED BY BETA EXCITATION IN TIN AND LEAD TARGETS

$$\int_W^{E_{\max}} N_b(W) dW = 2k \left(\frac{E_{\text{rms}}}{E_{\max}} \right)^2 Z E_{\max} \left(\log \frac{E_{\max}}{W} - 1 + \frac{W}{E_{\max}} \right) \text{ photons}/\beta. \quad (14)$$

The integral form allows a direct calculation of N_{bp} for any beta source and target, i.e.,

$$N_{bp} = N_b(W_1, W_2) = \int_{W_1}^{W_2} N_b(W) dW.$$

Depending on the source-target geometry, a fraction G of the bremsstrahlung high energy tail, N_{bt} , with photon energies above the K absorption edge, W_{ab} , may be absorbed by the photoelectric process, producing a characteristic x-ray component, N_{fl} , due to fluorescence excitation, i.e.,

$$N_{fl} = \omega_K G N_{bt} = \omega_K G \int_{W_{ab}}^{E_{\max}} N(W) dW \quad (15)$$

where ω_K is the K-shell fluorescence yield for the target material. Values of ω_K , as calculated by Burhop,¹³ are shown in Table V as a function of atomic number Z . For tin and lead, ω_K has been assumed to be unity in the present analysis.

2. K-Shell Ionization Characteristic X-Rays

Analogous to the bremsstrahlung treatment, the contribution of N_{ks} , the number of photons due to K-shell ionization by a beta particle, has been investigated by graphical integration over the beta spectra of interest as well as by deriving approximate analytical relations. In

TABLE V

 $\omega_K(Z)$ - K FLUORESCENCE YIELD VS ATOMIC NUMBER

Z	-	10	20	30	40	50	60	70	80
ω_K	-	0.02	0.14	0.46	0.71	0.84	0.90	0.93	0.95

general form

$$N_{ks} = \int_0^{E_{\max}} \phi_k(E) \mathcal{N}(E) dE \quad (16)$$

where $\mathcal{N}(E)$ is the normalized beta energy distribution and $\phi_k(E)$ is the thick target K x-ray production for an electron of energy E , given by

$$\phi_k(E) = \omega_K \int_{W_{ab}}^E \sigma_K(E) \left(\frac{dR}{dE} \right) dE. \quad (17)$$

A close study of the literature on ionization theory has led us to expect that the cross section for K shell ionization, $\sigma_K(E)$, is nearly constant with electron energy. Our preliminary results for this cross section, which include relativistic effects, are shown in Fig. 24. There are reasons to believe that the cross sections may increase even more markedly for very fast particles, finally reaching a plateau value when the polarization effect becomes pre-dominant.

Treating σ_K as independent of electron energy for energies above W_{ab} , as suggested by the curves in Fig. 24, equation (17) becomes

FIG.24-THEORETICAL K SHELL CROSS SECTIONS σ_k , AND RESIDUAL RANGE R , FOR MONOENERGETIC ELECTRONS

$$\phi_K(E) \approx \omega_K \sigma_K [R(E) - R(W_{ab})] \text{ photons/electron} \quad (18)$$

where $R(E)$ is the range for an electron of energy E .

From cross section σ_K and electron ranges R , as illustrated in Fig. 24, values were derived for $\phi_K(E)$ and N_{ks} for tin and lead using graphical integration with promethium-147, krypton-85 and yttrium-90 normalized beta spectra. The results for N_{ks} , expressed in percent K photons/ β , are shown in Fig. 23 for tin and lead targets.

We have recently found that similar results can be calculated directly, after further simplification of the formulae in terms of Z and $E_{\max}$. Thus, the calculated ionization cross section σ_K in Fig. 24 for near relativistic particles (at $E/mc^2 = 1$, or $E = 0.51$ Mev for electrons) turns out to be closely approximated by

$$\sigma_K \sim 10^6 Z^{-4} \text{ cm}^2/\text{gm} . \quad (19)$$

For energetic electrons, in the Mev region, the range-energy relationship is linear (Feather's Rule), i. e., $R(E) \sim 0.54 E - 0.16 \text{ gm/cm}^2$. For electrons of lower energy (< 0.1 Mev), a power law is applicable, e. g., $R(E) \sim 1.5 E^2 \text{ gm/cm}^2$. Using these expressions the thick target x-ray yield $\phi_K(E)$ for monoenergetic electrons can be expressed directly in terms of Z and electron energy E . To derive N_{ks} in relation (16), integration over the beta spectrum can also be avoided, using instead appropriate weighting functions. For energetic beta emitters in which the energy term is linear, we suggest the weighting factor $(E_{av}/E_{\max})$, and for soft beta emitters, the presence of E^2 suggests the weighting factor $(\frac{E_{rms}^2}{E_{\max}^2})$. Thus, we expect

$$N_{ks} \sim 5.4 \times 10^5 \left(\frac{E_{av}}{E_{max}} \right) \omega_K Z^{-4} E_{max} \text{ photons}/\beta \quad (20)$$

when $E_{max} \geq 1 \text{ Mev}$

$$\text{and } N_{ks} \sim 1.5 \times 10^6 \omega_K Z^{-4} \left[\left(\frac{E_{rms}}{E_{max}} \right)^2 E_{max}^2 - W_{ab}^2 \right] \text{ photons}/\beta \quad (21)$$

when $E_{max} \leq 0.1 \text{ Mev.}$

3. Geometry Effects on Photon Production

The importance of geometrical parameters of an isotopic x-ray source in determining the x-ray production have been pointed out and discussed above. Mainly, the target thickness determines the number of K x-rays produced directly by betas since the function $A_\beta(W, t)$ in equation (2) governs the manner in which the production function $N(W)$ goes to its asymptotical value at increasing target thickness.

Geometrical source parameters are of even greater importance in the production of fluorescent radiation since they govern both the production rate of bremsstrahlung photons and their subsequent conversion into fluorescent radiation.

An analytical method for the evaluation of a "geometrical factor" G equivalent to the term G in formula (15) appears extremely complicated especially when anisotropy of high energy bremsstrahlung photons and scattering of betas and x-rays are considered.

Geometrical dependence of the fluorescence component N_{fl} can be examined at least qualitatively in the following manner. For

sandwich beta excited x-ray sources, viewed normally to the slab surface, a fraction of the betas which produce the x-rays are those travelling in directions which make small angles to the surface of the slabs. The bremsstrahlung tail, N_{bt} , consists predominantly of photons which preserve the directions of their parent beta particles. With lateral slab dimensions large compared to the photon mean free paths, there will be extensive self-absorption in these directions, giving rise to isotropic fluorescent x-rays after the photoelectric absorptions. Essentially the same argument can also be made for the production of K peak photons by layers of source-target mixtures, again assuming that the lateral source dimensions are $\gg 1/\mu_x$.

One may conclude that the fluorescent radiation plays an important role in the total value of the production function $N(W)$ in those geometrical configurations allowing a large path length for the high energy bremsstrahlung photons in most directions. Total values of $N(W)$ should always be intermediate in between those determined by the extreme conditions: $G = 0$ (total escape of the bremsstrahlung tail from the source) and $G = 1$ (total absorption of the bremsstrahlung tail).

C. Calculated K Peak Photon Intensities

Results of the analytical procedures developed above and expected results of tin and lead targets bombarded by beta sources ranging in energy from carbon-14 to rhodium-106 are shown in Tables VI and VII.

The bremsstrahlung peaking, N_{bp} , and K shell ionization components of the K photon peak are shown directly in Table VI. The bremsstrahlung tail, N_{bt} , is useful for estimating both the contribution of

TABLE VI
CALCULATED BETA EXCITED PHOTON PRODUCTION

Source	$E_{\max}$ Mev	R mg/cm ²	Sn(Z = 50)			Pb(Z = 82)		
			N_{pb}	N_{bt}	N_{ks}	N_{pb}	N_{bt}	N_{ks}
			percent photons/ β			percent photons/ β		
C ¹⁴	0.14	25	0.08	0.15	0.16	0.07	0.03	0.01
Pm ¹⁴⁷	0.22	50	0.13	0.36	0.40	0.14	0.15	0.06
Kr ⁸⁵	0.67	250	0.46	2.0	2.0	0.56	1.7	0.2
Y ⁹⁰	2.2	1100	1.5	10.7	6.6	1.9	11.5	0.7
Pr ¹⁴⁴	3.0	1600	2.0	15	9.0	2.6	17.5	1.0
Rh ¹⁰⁶	3.5	1900	2.4	18	10.5	3.2	22	1.4

Formulae Used:

$$N_{bp} \approx 2k \left(\frac{E_{rms}}{E_{\max}} \right)^2 Z \left(\frac{E_{\max}}{W} - 1 \right) (W_2 - W_1) \text{ photons}/\beta \quad (22)$$

$$N_{bt} \approx 2k \left(\frac{E_{rms}}{E_{\max}} \right)^2 Z E_{\max} \left(\log \frac{E_{\max}}{W_{ab}} - 1 + \frac{W_{ab}}{E_{\max}} \right) \quad (23)$$

$$N_{ks} \approx 5.4 \times 10^5 \left(\frac{E_{av}}{E_{\max}} \right) \omega_K(Z) Z^{-4} E_{\max} \quad \text{when } E_{\max} \geq 1 \text{ Mev} \quad (24)$$

$$\text{and } N_{ks} \approx 1.5 \times 10^6 \omega_K(Z) Z^{-4} \left[\left(\frac{E_{rms}}{E_{\max}} \right)^2 E_{\max}^2 - W_{ab}^2 \right] \quad \text{when } E_{\max} \leq 0.1 \text{ Mev} \quad (25)$$

Values Used: $k = 7 \times 10^{-4} \text{ Mev}^{-1}$; $\frac{E_{rms}}{E_{\max}} = 0.45$; $\frac{E_{av}}{E_{\max}} = 0.33$; $\omega_K = 1$.

TABLE VII
EXPECTED PERFORMANCE OF SANDWICH SOURCES

Source	t_{opt} mg/cm ²	<u>Sn</u>		t_{opt} mg/cm ²	<u>Pb</u>	
		Y_k (% K/ β)			Y_k (% K/ β)	
		G = 1	G = 0		G = 1	G = 0
C ¹⁴	9	0.35	0.22	15	0.11	0.08
Pm ¹⁴⁷	15	0.73	0.44	25	0.34	0.19
Kr ⁸⁵	36	2.5	1.4	79	2.0	0.60
Y ⁹⁰	58	4.9	2.2	185	8.8	1.6
Pr ¹⁴⁴	62	5.0	2.1	220	11.6	2.0
Rh ¹⁰⁶	64	5.5	2.3	235	13.7	2.4

Formulae Used:

$$t_{opt} = \frac{\lg(\mu_{\beta} + \mu_x) - \lg 2\mu_x}{\mu_{\beta} - \mu_x} \quad (26)$$

$$Y_k = \frac{N}{2} \left[\frac{\mu_{\beta}}{\mu_{\beta} - \mu_x} (e^{-\mu_x t} - e^{-\mu_{\beta} t}) + \frac{\mu_{\beta}}{\mu_{\beta} + \mu_x} e^{-\mu_x t} \right] \text{ photons}/\beta \quad (27)$$

$$N = N_{bp} + N_{ks} + G N_{bt} \quad (28)$$

fluorescence radiation, N_{fl} , and also the "purity" of the K peak.

Two sets of values are shown in Table VII for the final yield Y_k of K photons per beta particle at optimum thickness of sandwich targets, corresponding to the extreme values $G = 0$ and $G = 1$ of the geometrical factor. It may also be seen that for low energy beta sources and lead targets the extent of fluorescence contribution has a minor effect on the K yield, while for high energy sources it is the critical parameter. For tin targets the fluorescence effect appears to be nearly the same for all of the beta sources considered; the K photon yield only changes by a factor of two between $G = 0$ and $G = 1$.

D. Comparison with Experiments

In comparing the K photon yield values in Table VII with the observed values in Table I we find that the agreement is very encouraging. The measured values are in general intermediate between those given in Table VII for maximum and minimum fluorescence excitation. Since all of our sources were encapsulated, such that there was an appreciable distance between the source and target material, the yield values are consistent with low contributions from fluorescence excitation. The agreement between calculated and experimental values of yield suggests that the analysis gives absolute K photon yields correct to better than a factor of two.

Only preliminary evaluations have been made of the x-ray "purity" (the ratio of photon yield in the K peak to the total number of photons in the high energy bremsstrahlung tail). For sandwich sources an upper limit for this parameter was estimated as the ratio Y_k/N_{bt} , using values from Tables VI and VII. The resultant values decrease as the beta energy increases, agreeing with experimental data that low energy sources such as

promethium-147 in general give the highest K line purity. The observed increases in purity for reflection and 90° geometries and reduced purity for transmission geometries have not been treated. This may become amenable to quantitative treatment after the anisotropy factors and the bremsstrahlung spectrum are determined more fully.

V. APPLICATIONS OF EXPERIMENTAL AND ANALYTICAL RESULTS TO HIGH-LEVEL SOURCE DESIGNS

A. General Remarks

The experimental information and the results of the analysis described above furnish a basis for designing an isotopic x-ray source. Optimum external target thicknesses can be calculated for a wide range of β -energies and target materials. X-ray yields for these optimum conditions may also be anticipated to within a factor of two. On the basis of the results of previous sections one can also evaluate the order of magnitude of the maximum x-ray output obtainable by an isotopic source.

Maximum output is obtained with configurations corresponding to optimum target dimensions, but limitations exist due to the finite specific activity of the β -emitter and to the desired size of isotopic source. Using external targets, the thickness of the β -source, including encapsulation, must be small as compared with the maximum β -range. If a small x-ray focal spot is desired, the volume of the β -emitter and the maximum x-ray output is limited. When large area x-ray sources are acceptable or desired, a limit in the x-ray output is determined only by the area of the x-ray source, and a high x-ray flux can be achieved.

As in the external target geometries, a limit in the maximum x-ray output per unit of source area also exists for the source-target mixtures.

Here, however, the x-ray output is an asymptotic function of the source thickness, and considerations of costs of beta emitter and source fabrication can indicate which fraction of the x-ray saturation output is most convenient to achieve.

In designing an isotopic x-ray source, the desired x-ray spectral distribution is the major factor in the choice of the beta emitter. The experimental and analytical results of the previous paragraphs indicate that K peak yield and "purity" depend strongly on beta energy. For x-ray outputs peaking at characteristic radiation of medium Z targets (from zirconium to tungsten) the low energy beta emitters are the most advantageous. For high Z targets (lead, uranium) only the high energy beta emitters give a high yield of x-rays. Although high energy betas produce, in general, a large amount of high energy bremsstrahlung, the peak purity is, at least for high Z targets, satisfactory for most of the source applications.

It is our feeling that, as far as K x-ray yield and purity is concerned, one should follow the general rule of high energy beta emitters combined with high Z targets and low energy betas with medium Z targets. This rule is, however, referred to the design of compact isotopic sources. When a large size x-ray source can be tolerated, there exists more flexibility in beta emitter-target combination as one may realize from the x-ray spectra shown in Fig. 7 for a strontium-90 beta source with the medium Z tin targets. This figure shows that a substantial improvement in peak purity can be obtained if a loose geometric configuration, such as the 90° reflection target, can be used.

With the aid of our experimental study and analytical formulations of x-ray yield and optimum target parameters, we investigated the specific

design of some isotopic x-ray sources using the three beta emitters considered in this work. It must be understood that the cases we have considered are not the only possible solutions, but they are representative of good utilization of the three beta emitters for high level x-ray source designs. Two of these sources have been actually constructed and their performance tested in some typical x-ray applications described in the following section.

B. Strontium-90 Source Design

As discussed above, we considered the strontium-90 a very suitable beta emitter for an isotopic x-ray source using high Z target material in a sandwich geometry.

Two alternative source assembly designs can be followed. If x-ray distributions peaking at different energies (in the 50-100 Kev range) are desired, the beta source can be assembled as a separate unit sealed by two thin windows. This unit can be sandwiched between a pair of targets of a metal chosen according to the desired energy of K x-rays. If the isotopic source is designed for a specific application requiring only one particular x-ray distribution, the two targets of the sandwich assembly can be parts of the capsule itself. This can be eventually sealed in a low Z metal container (aluminum or stainless steel) provided with a thin window, if the target metal does not allow a reliable seal.

For both the suggested sandwich target assemblies, the back target should be of thickness sufficient to stop the betas completely. For the front target, optimum thickness is given by relation (8) in Table II. Treating the specific case of an x-ray spectrum peaking at about 100 Kev (uranium target), and using the values of $\mu_{\beta} = 8/1100 \text{ cm}^2 \text{ mg}^{-1}$ and $\mu_x = 1/1000 \text{ cm}^2 \text{ mg}^{-1}$,

the relation (8) gives $t_{\text{opt}} = 230 \text{ mg cm}^{-2}$.

A high level x-ray source will require a large amount of beta emitter distributed in a thick layer in between the pair of metal targets. This implies a considerable self-absorption of betas in the source itself. Due to the exponential absorption of a beta spectrum, the beta flux from a thick source can be expressed by a relation similar to (9) used for the x-ray yield from a uniformly distributed x-ray source. However, if this expression is used to represent the effective number of betas available for the production of x-rays in external targets, an under-estimate of x-ray output will result since the beta self-absorption affects mostly the low energy part of the spectrum which is the less effective in photon production. The unabsorbed betas of strontium-90 and the radiation produced in the energy range of the target K peak by beta self-absorption should equal the moderate attenuation of yttrium-90 betas in a source layer of the order of a few hundreds of mg cm^{-2} . Thus, in designing an isotopic x-ray source using a thick beta layer of strontium-90 yttrium-90, one may consider the yttrium-90 as the only "effective" beta source for x-ray production in an external target.

A strontium-90 source material very suitable for this type of x-ray source design seems to be the SrTiO_3 manufactured in the form of very stable ceramic pellets by ORNL. For a beta source thickness equivalent to two relaxation lengths ($\sim 300 \text{ mg cm}^{-2}$) and with the specific activity of 40 curies per gram of ceramic compound, an "effective" beta activity of about 12 curies per unit of source area is expected.

The K x-ray output, evaluated by the relation (7) for $t_{\text{opt}} = 230 \text{ mg cm}^{-2}$ and a beta activity of 12 curies per unit of area, turns out to be:

$$\mathcal{N}_x = 0.65 N(W) 12 \cdot 3 \cdot 7 \cdot 10^{10} \sim 3 \cdot 10^{11} N(W) \text{ photons/sec} \quad (29)$$

where $N(W)$ is the x-ray production function by betas. This can be evaluated by using the expressions summarized in Tables VI and VII. For a K x-ray energy range from 80 to 120 Kev, the expressions (22), (24) and (23) give for the three components of the production function $N(W) = N_{bp} + N_{ks} + G N_{bt}$ the following values:

$$N_{bp} \text{ (bremsstrahlung peaking)} = 2.2 \cdot 10^{-2} \text{ photons/beta}$$

$$N_{ks} \text{ (K-shell ionization)} = 0.45 \cdot 10^{-2} \text{ photons/beta}$$

$$N_{bt} \text{ (bremsstrahlung tail)} = 11.5 \cdot 10^{-2} \text{ photons/beta.}$$

Then the yield of K x-rays should have a value intermediate between 1.7 and 9 percent x-rays per beta. These are the extreme values corresponding to minimum ($G = 0$) and maximum ($G = 1$) contribution of fluorescent radiation due to photoelectric absorption of the high energy bremsstrahlung tail.

The comparison between calculated and experimental values of x-ray yield in the similar case of lead target (see Table I and VII) suggests that a K x-ray yield of about 4 percent photons per beta should be observed for the combination strontium-90 and uranium target considered.

Thus the K x-ray output should have the value:

$$\mathcal{N}_K = 3 \cdot 10^{11} \cdot 4 \cdot 10^{-2} \sim 1.2 \cdot 10^{10} \text{ photons/sec} \quad (30)$$

or about 25 "mc" of K photons per curie of the beta emitter. This corresponds to a flux of K x-rays per cm^2 at one foot distance of about

$$\phi_K = N_K \frac{\Omega}{4\pi} = \frac{1.2 \cdot 10^{10}}{30.5^2 4\pi} = 10^6 \text{ K photons/sec,} \quad (31)$$

and a dose rate of about 200 mr/hr at one foot. This has to be compared with dose rates of the order of 1 r/sec at one foot given by conventional x-ray apparatuses for deep dose therapy or industrial radiography, operating at 10 mA and 200 KVP, with filtration which insures an x-ray energy distribution of attenuation equivalent to that of the strontium-90 uranium source (half value layer about 2 mm of copper). A major improvement of x-ray output is expected through the use of beta source material of higher specific activity.

The spectral distribution of x-rays from a strontium-90 source with uranium target is quite similar to that obtained with lead target. Figure 25 shows the x-ray spectra obtained with a uranium sandwich geometry using the 10 mc strontium-90 source described in the previous section. The energy distribution of x-rays exhibits a K peak of high purity, with a ratio of about 1:1 for the K peak and the bremsstrahlung tail components. This spectral distribution and the x-ray flux that can be obtained suggest that this source should be particularly suited to thickness gaging, industrial radiography and composition analysis by backscattering technique. Its performance is expected to be quite similar to that of the 129 day gamma emitter Tm^{170} with the advantage of a much longer half-life. The cost of the x-ray output from the strontium-90 and high Z targets is moderate, of the order of one dollar or less per mc of K photons.

C. Krypton-Strontium Source Design

The results of our study and some considerations on the physical form of krypton-85 seem to limit the possibility of a compact high level

FIG.25-X-RAY SPECTRA FOR Sr^{90} -URANIUM TARGET SANDWICH AND Kr^{85} WITH LEAD CONE TARGET

x-ray source using this isotope and external targets geometry. With the source material of $\sim 80 \text{ mc/cm}^3$ available at the present, even a relatively high pressure beta source contained in a capsule made out of a proper target material, total beta activity and x-ray output are still below those obtainable for the same source size with the strontium-90 and promethium-147. However, valuable features of this β -emitter, such as the easy handling and the insignificant biological hazard in case of leakage or rupture of a source, justify the growing interest and research on this isotope. This has already led to the possibility of confining krypton-85 in clathrates¹⁴ with a specific activity of several curies per gram of compound, which is indeed a valuable technical advance in the problem of compact krypton-85 sources.

The K x-ray output using external targets may be quite limited, however, due to the attenuation of the betas in the clathrate itself. The best results with clathrates should be obtained if the target element can be incorporated in the clathrate itself or with mixtures of powdered clathrate and target material. High level x-ray sources using krypton-85 are limited also by the presence of a 0.54 Mev gamma component. For every curie of krypton-85, this radiation, despite the low intensity of 0.7 percent per beta particle,¹⁸ will give an exposure dose of about 20 mr/hr at one foot; this means that effective shielding is required for biological protection if a large amount of this isotope is used.

It is our feeling that this isotope can provide x-ray sources of moderate level for use in research and technical application if the source size is not of a special concern and the gamma component can be tolerated.

A source design which is amenable to a variety of geometrical arrangements with external target consists of a cylindrical thin walled

container filled with krypton-85 in gaseous form. In Fig. 26 three typical geometries are indicated. In A the beta source is inserted into a pipe of the target material, a situation analogous to the sandwich configuration for a point or a flat beta source. In B the beta particles produce in a cap target a rectangular x-ray source of adjustable width. In C the conical target produces a conical beam of x-rays of a cross section determined by the aperture of the cone.

Two of these sources were constructed, one containing about 25 mc and a second containing 500 mc of krypton-85. The cylindrical containers were a thin electrolytic nickel tube 0.25 inch in diameter, 4 inches in length, with a wall thickness of approximately 0.0015 inch. The two sources were constructed by the Nuclear Chicago Corporation and were subsequently enclosed in a shield constructed in our machine shop. Figure 27 shows the schematic of this type of beta source with its container from which the source can be ejected after a cone or pipe target is applied to one end of the shield.

The 500 mc source was designed for testing the performance of this type of source in some technical applications. A 25 mc source was judged to be of a strength suitable for a study of the spectral distribution of x-rays produced in different geometries and with various target materials. Spectral distributions obtained with cone and pipe target configurations were studied with a scintillation detector in connection with a pulse height analyzer.

Figure 28 shows the spectra observed with different metal cone targets of "infinite" thickness for the betas ($t > R_{\max}$). The zirconium

FIG.26- Kr^{85} X-RAY SOURCE ARRANGEMENTS

FIG.27- KRYPTON-85 SOURCE ASSEMBLY

FIG.28- X-RAY SPECTRA FROM Kr^{85} WITH DIFFERENT CONE TARGETS.

and tin targets show the cleanest x-ray peak distributions. The lead cone gives a spectrum with a broad continuum between the K and L radiation peaks. Using a 90 mg/cm^2 lead filter and a lucite beta stopper, both located at the base of a conical lead target, a well filtered spectrum has been obtained without reduction of the K x-rays. This spectrum is shown in Fig. 25 together with that of strontium-90 with a uranium sandwich target for comparison of K peak purity.

The similarity of those spectra suggests again that krypton-85 does not present any advantage with respect to strontium-90 for a clean peak distribution of x-rays from high Z targets. For medium Z elements, however, the cone target exhibits clean K peaks and relatively high yields.

Figure 29 shows the x-ray spectra obtained with pipe targets of thicknesses chosen to be near the optimum thickness expected for sandwich geometry and reported in Table VII. As with the cone targets, the K peaks seem to be quite prominent. It must be mentioned, however, that the K x-ray peak of lead, the bremsstrahlung tail and the gamma line have approximately equal intensity if efficiency and scattering in the x-ray detectors are taken into account. For medium Z pipe targets the K peak purity is reduced. Thus, the cone target configuration appears to be the most desirable for krypton, giving an x-ray source of valuable flexibility and useful output when large beams of x-rays are desired. The x-ray flux has been found fairly constant across the beam in an area intercepted by the aperture of the conical target. The main field of application of such a source should be thickness gaging by absorption and fluorescent radiation measurements.

FIG.29- SCINTILLATION COUNTER SPECTRA FOR Kr^{85}
WITH Sn AND Pb PIPE TARGETS

Maximum x-ray output from a krypton-85 isotopic source depends on the dimensions of the beta source and on the level of gamma component that can be tolerated. It is felt that sources containing about 10 curies of beta emitters (with 70 mc of 540 Kev gammas) will not present a tremendous shielding problem in most uses. Source size for 10 curies of beta emitter should also be in the same range of our prototype source, especially if krypton with a higher specific activity can be obtained. The K x-ray flux for 10 curies of krypton-85 and a lead target in the cone geometry described above, should be of the order of 10^5 photons/cm² per sec at one foot on the axis of a conical beam. With this x-ray output and a cost of \$15 per curie of beta emitter, the cost per mc of K photons will be of the order of \$5.

D. Promethium-147 Source Designs

As previously discussed, for the best utilization of this beta emitter, a medium Z target material should be used in an intimate beta source target mixture. Maximum x-ray output will be obtained by the use of the "pure" beta emitter with, however, a fixed energy for the x-ray peak, i. e., the promethium K x-ray (38.5 Kev).

An estimate of the maximum x-ray level obtainable from such a source can be made by using the proper formulation of x-ray production function and yield variation reported in Tables II and VI. For maximum x-ray output from a source of limited area, the relation (9) indicates that there is little advantage in using a source thickness exceeding three relaxation lengths for the promethium K x-ray in the source compound. Assuming the promethium oxide as a suitable material for source fabrication, the ~38.5 Kev K radiation of promethium has $1/\mu_x \sim 220$ mg/cm².

The x-ray output for a source of unit area, thickness t and specific activity A is given by relation (9), i. e.,

$$\mathcal{N}_X = A t N(W) \frac{1 - e^{-\mu_x t}}{\mu_x t} \text{ photons/sec.} \quad (32)$$

The promethium-147 material now available has a maximum specific activity of about 400 curies per gram. For a source thickness of $3/\mu_x = 650 \text{ mg cm}^{-2}$, about 250 curies of beta emitter are required. Thus (32) becomes:

$$\mathcal{N}_X = 3.0 \cdot 10^{12} N(W) \text{ photons/sec.} \quad (33)$$

The photon production in the K peak, calculated by the relations (22), (24) and (23) in Table VI, gives for a K x-ray range from 30 to 50 Kev the values:

$$N_{bp} \text{ (bremsstrahlung peaking)} \sim 1.6 \cdot 10^{-3} \text{ photons/beta}$$

$$N_{ks} \text{ (K-shell ionization)} \sim 1.0 \cdot 10^{-3} \text{ photons/beta}$$

$$N_{bt} \text{ (bremsstrahlung tail)} \sim 2.9 \cdot 10^{-3} \text{ photons/beta}$$

Since the source dimensions are much larger than $1/\mu_x$, a fraction of the high energy bremsstrahlung tail should be converted to fluorescent radiation. Assuming for $N(W)$ the value $4 \cdot 10^{-3}$ photons/beta, intermediate between those corresponding to maximum and minimum contribution to fluorescent radiation, the K x-ray output of the source should be

$$\mathcal{N}_K = 3.0 \cdot 10^{12} \cdot 4 \cdot 10^{-3} = 1.2 \cdot 10^{10} \text{ K photons/sec} \quad (34)$$

or about 1 mc of K photons per curie of betas. This should represent the maximum x-ray output obtainable from a unit area of a "pure" promethium

147 source. The source should give per cm^2 at one foot distance a K x-ray flux:

$$\phi_K = 1.2 \cdot 10^{10} \frac{\Omega}{4\pi} = \frac{1.2 \cdot 10^{10}}{4\pi \cdot 30.5^2} = 10^6 \text{ K photons/sec} \quad (35)$$

and a dose rate of about 300 mr/hr at one foot. This has to be compared with dose rates of the order of 5 r/sec at one foot given by conventional x-ray apparatuses for deep dose therapy or industrial radiography, operating at 10 mA and 160 KVP, with filtration which insures an x-ray energy distribution of attenuation equivalent to that of the promethium-147 source (half value layer about 4 mm of aluminum).

With the current price of \$3.25 per curie of promethium-147, the cost of the x-ray output for this source is of the order of \$3 per mc of photons.

A prototype high level promethium-147 source has been designed according to the above estimate and prepared by the ORNL. The source was a disk source of one cm in diameter encapsulated in a brass container provided with a beryllium beta stopper and a thin stainless steel window for the x-ray exit. Figure 30 shows the source assembly. A reduction in size of the x-ray beam down to a focal spot 2 mm in diameter was obtained by replacing the cover cap C with an equivalent one made out of lead and provided with a conical diaphragm. On the basis of the above data, for a 1 cm^2 in diameter disk, 200 curies of source material were required. About 200 curies of promethium oxide were compressed in a die to form a compact disk that was fired in order to obtain a ceramic element.

Technical difficulties arising during fabrication of this prototype source led to a disk 7 mm in diameter, giving about twice the thickness and

FIG. 30- PROMETHIUM-147 SOURCE ASSEMBLY

one-half the source area indicated above. The source produces an x-ray flux of $\sim 3 \cdot 10^5$ K photons/cm²/sec at one foot. This is in very good agreement with the expected flux when source area and window attenuation are taken into account, and is about one-half the output expected for the same total activity and the optimized design. Spectral distribution of x-rays produced by this source is shown in Fig. 31.

The same procedure described above for the evaluation of x-ray output from a "pure" promethium source can be used for a mixture of promethium-147 with a target compound. In a limited range of target materials, with a value of Z close to that of promethium, the x-ray production function and relaxation length does not change drastically and the performance of a mixed source can be anticipated by using the results obtained for the pure promethium source.

As mentioned in a previous section, the x-ray energy distribution of a mixture of promethium-147 with a target material will depend on the ratio of the two elements (promethium and target) in which the x-rays are produced and self-absorbed. It is conceivable that a large concentration of promethium in the mixture with other elements of medium Z will result in a poor transmission and broadening of the desired x-ray peak distribution. The effect should be similar to that experienced with graded filters used to filter out a portion of an x-ray spectrum. We believe that a mixture of promethium-147 with target compounds should give the expected outputs and spectral distributions if the promethium does not exceed a few percent of the total source material.

When source area is not limited, larger x-ray yields and total output can be obtained from relatively thin sources of "pure" promethium-147.

FIG.31- X-RAY SPECTRUM FROM 200 CURIE Pm_2O_3 SOURCE

Optimum yields for a mixed source-target are given by thicknesses of the order of the maximum beta range ($R_{\max} = 50 \text{ mg cm}^{-2}$). By using the same procedure described above, one can evaluate the x-ray output expected from a layer of 50 mg cm^{-2} of source material. The results of this computation show that a source of 5 cm^2 , requiring about 100 curies of the beta emitter, should give about the same x-ray output of a "thick" source of one square cm and requiring 250 curies of promethium-147.

High level sources of K x-rays produced in external targets by promethium-147 betas seem to be precluded by the short range of the betas and the high Z of the promethium itself. The possible design of this type of source would be a thin ceramic coating ($5\text{-}10 \text{ mg cm}^{-2}$) of the beta emitter on a metal target, covered by similar metal foil in order to obtain a sandwich geometry. However, even for the small source thicknesses indicated above, a large fraction of the x-rays will be produced in the beta source itself rather than in the external target, contributing to a broad distribution of the x-ray spectrum.

The three beta emitters strontium-90, krypton-85 and promethium-147 have been chosen for this study because of their attractive features of long half life, high specific activity and large scale availability. The results obtained in this study and in particular the source design procedure described in some detail for the strontium-90 and promethium-147 beta emitters can be, however, applied to other isotopes and to a variety of x-ray source characteristics.

The present ORNL production of beta emitters offers a choice of several short-lived products. Due to their high specific activities, short-lived isotopes provide a means for the design of x-ray sources with orders

of magnitude greater intensity than those obtainable from strontium-90 and promethium-147 sources of equivalent physical size. It is our belief that, due to the time required for source fabrication, encapsulation, testing, etc., only isotopes with half-life greater than one month should be considered for the design of x-ray sources. For most x-ray applications a half-life of the order of one month is still inconvenient since a periodical recharging of the source will be necessary. It is conceivable, however, that in some special technical problems, a high level source operating for a short period of time will be desired. Sulfur-35 (87 days half-life, 0.167 Mev) and strontium-89 (50.4 days half-life, 1.46 Mev) look particularly attractive for the design of very high level and/or small size sources. However, the present high cost (of the order of one dollar per mc) and the present small rate of production of these and other short-lived isotopes limits the practical use of very high specific activity beta emitters.

VI. APPLICATIONS OF ISOTOPIC X-RAY SOURCES

The performance of the isotopic sources discussed in the previous sections have been investigated in some typical applications. The tests which were performed include: critical absorptiometry, quantitative and qualitative analysis by fluorescence excitation, mass thickness gaging by x-ray attenuation and radiographic inspection.

A. Critical Absorptiometry

When an x-ray beam passes through a material it undergoes attenuation which depends on the nature of the material, its thickness and the x-ray energy distribution. For an x-ray beam peaking at a given energy, the attenuation is, of course, enhanced if the absorber exhibits (at that energy)

a maximum absorption coefficient. This occurs for all elements at an x-ray energy equivalent to the binding energy of inner shell electrons. An x-ray spectrum peaking just above one of the absorption edges of an element yields a highly sensitive thickness measurement. In a mixture of several elements for a certain range of relative concentrations, the x-ray attenuation can be due primarily to the element whose absorption coefficient peaks at the energy of the x-rays adding the feature of selective measurement. Among the natural sources of electromagnetic radiation, isotopic x-ray sources present a unique flexibility in the choice of the x-ray energy distribution, determined by the atomic number of the target material.

Using critical absorptiometry, we considered the quantitative analysis of the silver content in photographic products. As a source of x-rays we used a mixture of promethium-147 with antimony oxide. The use of a low energy beta emitter ensures a relatively clean peak at about 26 Kev, characteristic K x-ray radiation of antimony. This energy is the best choice for critical absorption in silver whose K absorption edge is at 25.5 Kev. The significant parameters for optimum design of this type of source have been discussed previously (III E).

Measurements of x-ray attenuation by the silver content in photographic materials were made using a thin window NaI(Tl) scintillation spectrometer in conjunction with a pulse height analyzer. From this data, two sets of results were derived; the attenuation of the antimony K peak, and the attenuation of the integral x-ray spectrum. This was done in order to obtain information on the capability of the method when used with two different read-out systems, i. e., a single channel analyzer to measure the peak attenuation, and the more conventional and simple count rate

meter or scaler for the attenuation of total counts above a noise level.

Samples for this study were furnished by Eastman Kodak Company and included several standard photographic films and an x-ray film. For all the samples, the amount of silver per cm^2 was determined by chemical analysis.

The measurements showed that the x-ray attenuation was very nearly a linear function of silver thickness of the samples, as expected for a low range of silver thickness. Figure 32 shows the antimony K peak attenuation as a function of silver thickness. The experimental errors are derived from counting statistics.

As an illustration of this method of analysis we may discuss briefly the results in terms of the accuracy expected in routine testing of photographic products done with an adequate source strength and a counting time of one minute. An optimum source containing of the order of one curie of promethium-147 should give, for a one inch square detector and a source-detector distance of a few inches, a counting rate of the order of $\sim 2 \cdot 10^5$ cps, which is compatible with conventional electronics. For the extreme values of silver thickness (0.125 and 2.25 mg cm^{-2}) which were investigated, the percent x-ray attenuation and accuracy for one minute counting time would be 0.6 ± 0.07 and 11 ± 0.05 respectively at 90 percent confidence level. This is an accuracy of the order of 10 percent for the thinnest sample and a fraction of one percent for the thicker one. These results are referred to attenuation of the antimony K peak.

Integral counting data gives attenuations reduced to about 75 percent of the differential values quoted above. This technique would require

FIG. 32 - ANTIMONY K X-RAY ATTENUATION IN PHOTOGRAPHIC MATERIAL.

a slight increase in counting time for comparable accuracy.

The values of K peak attenuation are in close agreement with the attenuation expected from a sharp line of x-rays of energy equivalent to the K_{α} radiation of antimony. The agreement gives support to the results of the analysis of x-ray production by betas summarized in Table VI, showing that, for a medium Z target material, the characteristic radiation represents a major contribution to the observed spectrum.

We believe that the results observed in the case of silver can be extrapolated to many other combinations of absorber and x-ray target material satisfying the conditions of critical absorption discussed above. This suggests the possibility of using the absorptiometry technique as a method for nondestructive gaging and control of sheet materials during fabrication. In particular, photographic items seem worthy of consideration. In such applications, the use of ion chambers should be considered since larger detection areas are easily obtained and since the limitation on x-ray flux required for pulse analysis with a scintillation detector does not apply. Thus high sensitivities and accuracies can be achieved in short times. If larger areas can be averaged, response times less than a second can be achieved which will be highly desirable in a thickness control device.

Application of x-ray techniques to the gaging of silver in sensitized photographic materials brings up the problem of the effect of radiation dose on the fog level of the material. We investigated the increase in optical density from x-ray exposures sufficient to give an accuracy of better than one percent for one inch diameter samples. For an x-ray medical

film with about 4 mg/cm^2 of silver, the increase in optical density was about 0.02 or 10 percent of the optical density of unexposed film. This effect is within the limit which is considered tolerable provided that the increase in optical density is uniform. The possibility of testing small areas to locate small size defects in the silver emulsion has not been investigated. It seems, however, that much higher x-ray flux is required for this purpose and the feasibility of nondestructive testing using radiation depends mainly on the degree of sensitivity of the silver emulsion in the stage of fabrication during which the x-ray exposure is given.

B. Quantitative and Qualitative Analysis by
Fluorescence Excitation

Absorption of x-rays in matter is in great measure due to the photoelectric effect. When the process involves ionization of inner (K and L) atomic shells, the de-excitation occurs in part by electronic transitions with the emission of characteristic radiation of easily measurable energy. Energy and intensity measurements of this fluorescence radiation provides a qualitative and quantitative analysis of the absorbing medium. The low efficiency of the over-all process together with restrictions in the geometry and detection efficiency usually require high intensity x-ray sources for analysis.

The studies of isotopic x-ray source performance have been made with the high level, 200 curie promethium-147 source previously described. The spectral distribution of x-rays from this source is given in Fig. 31. With an x-ray spectrum peaking at about 38.5 Kev, the source is suited for excitation of K fluorescence in medium Z (< 56) elements and L fluorescence in the heavier elements. Figure 33 shows the experimental set up used for testing the performance of the source in this

FIG.33-EXPERIMENTAL ARRANGEMENT FOR SILVER FLUORESCENCE
X-RAY ANALYSIS

technique. The x-rays from the promethium-147 source produce fluorescence radiation in the sample which is seen by the x-ray detector through a lead collimator lined with cadmium and copper foils.

The x-ray energy analysis was performed using a NaI(Tl) scintillation counter and a gas flow proportional counter together with a multi-channel pulse height analyzer. Tests have been made using different sample elements. The compositional analysis of complex mixtures of elements has not been investigated since the feasibility depends more on the x-ray detectors than on the source characteristics.

1. Quantitative Analysis of Silver in
Photographic Materials

The fluorescence method has been tested in quantitative analysis of silver using the photographic products mentioned in the previous paragraphs. The evaluation of silver K fluorescence has been the same as described for the critical absorptiometry technique in that both the peak counting rate and the total x-ray spectrum were used as an indication of the capability of differential and integral measurements respectively.

Figure 34 shows the spectral distribution of x-rays from a thick (2.25 mg cm^{-2}) and a thin ($.287 \text{ mg cm}^{-2}$) silver coating normalized to the same peak amplitude, together with the spectrum due to the thin sample after chemical depletion of the silver halide. For both samples, the separation between the silver and bromine K peak is fairly good, and discrimination against bromine in a total spectrum detection by count-rate meter can be easily achieved. The spectrum of x-rays from the thin sample shows that the system detected both silver fluorescence radiation and scattered x-rays from the promethium source. For large silver thicknesses this background of scattered x-rays is negligible. For small

FIG.34 K X-RAY FLUORESCENCE OF PHOTOGRAPHIC FILMS OF DIFFERENT SILVER THICKNESS.

thicknesses, however, better sensitivity is achieved by subtraction of this background due to the low Z plastic and gelatine base materials. Figure 35 shows the dependence of the K peak intensity on the silver thickness. Data for the silver K peak is the difference in reading between a sample with its original silver coating and a depleted sample of the same lot. The statistics are of the order of a fraction of one percent for all the samples we used and counting times were one minute. The results shown in Fig. 34 suggest that the sensitivity of this method of analysis could be considerably improved by the use of a higher resolution x-ray detector to minimize the effect of scattering. The use of a krypton proportional counter, for instance, should give very good discrimination of the silver peak from the scattering peak observed for thin samples and permit a single counting measurement even for low silver content.

2. Film Badge Readout

Fluorescence analysis has also been investigated as a method of reading developed film dosimeters exposed to a wide range of radiation doses. The amount of silver remaining in film dosimeters after processing is related to the radiation dose. The film blackening due to this silver is usually measured with an optical densitometer giving an evaluation of the radiation dose. However, for large doses the optical density may exceed the limit of densitometers.

A technique for reading high accidental doses has been described recently by W. V. Baumgartner¹⁵ who states that doses exceeding optical density three can be determined by measuring the silver fluorescence radiation using an x-ray apparatus and a crystal diffraction

FIG. 35 - SILVER FLUORESCENCE INTENSITIES OF PHOTOGRAPHIC FILMS

spectrometer. Using the arrangement shown in Fig. 33, we measured the residual silver in developed Dupont type 555 dosimeter film exposed to 40 Kev x-ray doses ranging from one to 125 R and cobalt-60 gamma-ray doses from 10 mr to 10,300 R. Table VIII shows the results of our measurements. For direct correlation of reading with dose, the data have been corrected for the background dose reading given by an unexposed film dosimeter of the same batch developed together with the exposed dosimeters. This is a standard procedure in film dosimetry which permits an estimate independently of the dose accumulated from the time of manufacture to time of the processing due to the normal radiation environment.

Low doses were more carefully studied with x-ray exposed films. For this set of data Table VIII reports the readings for background dosimeters and depleted films, averaged over four samples of each type. The readings for each group were found to be within the statistical error indicated for the average readings. The comparison of background and depleted film reading shows that the dosimeters accumulated a radiation dose equivalent to approximately 3 mr of 40 Kev x-rays or 50 mr of hard gammas. This is not surprising since these tests were made with 3-4 month old films. Our measurements show that in spite of this high background, an additional dose as low as 1 mr of x-rays gives a reading substantially in excess of the statistical errors.

Figures 36 and 37 are graphical representations of the data of Table VIII. The slope of the curves at high dose suggests that the method may be used to measure even higher exposures than those investigated, covering (both for x-rays and gamma-rays) a range of at least six decades of exposures. For comparison of the exposure range covered by this method

Table VIII

INTENSITIES OF SILVER FLUORESCENCE RADIATION
FROM DEVELOPED FILM DOSIMETERS

X-Ray Exposures		Gamma-Ray Exposures	
Dose(r)	Silver K Peak cpm	Dose(r)	Silver K Peak cpm
125	94900 $\pm$ 570	10300	104880 $\pm$ 590
11.8	87120 $\pm$ 550	2575	98220 $\pm$ 570
2.64	81480 $\pm$ 530	650	95700 $\pm$ 560
0.56	64440 $\pm$ 490	115	88440 $\pm$ 550
0.096	27900 $\pm$ 380	9.1	64820 $\pm$ 480
0.015	7810 $\pm$ 300	1.0	26730 $\pm$ 360
0.005	2450 $\pm$ 250	0.12	5100 $\pm$ 210
0.0025	1880 $\pm$ 215	0.04	1570 $\pm$ 185
0.001	1150 $\pm$ 210	0.02	970 $\pm$ 180
		0.01	320 $\pm$ 175
Background Film 7500 $\pm$ 145			
Depleted Film 5600 $\pm$ 125			

with that of optical densitometers, Figures 36 and 37 indicate the exposures giving an optical density of five. These can be considered as the upper limit of densitometers used in routine work. The exposures giving an optical density of 0.05, which is the lower limit for reliable readings, are also marked to indicate the extension of the lower limit. These results clearly indicate that the fluorescence method, even in the simple arrangement used for these experiments, can extend the range of radiation dose measurements to high accidental doses and can measure with good accuracy low doses for which the optical methods are unreliable.

The use of an x-ray source especially designed for this purpose, with higher x-ray output and smaller physical dimensions should lead to a greater production of silver fluorescence. This will permit a high measurement accuracy with improved collimation of the observed radiation. Thus, it should be possible to measure the radiation exposure to the various portions of a film dosimeter exposed under different radiation filters, and thereby obtaining the readout flexibility consistent with current practice.

3. X-Ray Fluorescence of High Z Elements

The performance of the promethium-147 x-ray source has also been tested in the detection of heavy elements by the fluorescence method. As pointed out, the source exhibits a spectrum peaking at 38.5 Kev and only L fluorescence radiation will be observed for elements of Z greater than 56 (barium). For this demonstration, we used the same experimental arrangement shown in Fig. 33 with a proportional counter as the x-ray detector. The detector was a 4 inch diameter flow type counter with thin mylar windows for efficient low energy x-ray detection. The counter was

FIG.36 - SILVER FLUORESCENCE INTENSITY VS X-RAY DOSE IN FILM DOSIMETERS

FIG.37- SILVER FLUORESCENCE INTENSITY VS GAMMA-RAY DOSE IN FILM DOSIMETER

operated with P-10 gas at standard pressure.

The detection of lead and mercury on paper air filter was chosen as an example of heavy element detection. This is an important technological problem in the monitoring of air contamination in mines and industrial use of poisonous heavy elements. A sample of filter paper loaded with dust containing lead was obtained from Mine Safety Appliance Company. The amount of lead has been estimated as approximately 0.8 mg cm^{-2} . As expected from the results obtained with photographic products, the x-ray spectral distributions show the contribution of L_{α} and L_{β} fluorescence of lead superimposed on a background of scattered radiation. Figure 38 shows two x-ray spectra for the sample containing lead. The higher spectrum is that directly observed by our detection system; the lower is the same after correction for background observed with a sample of blank filter paper. Neither curve is corrected for counter efficiency. Figure 39 shows similar spectra obtained with a filter paper loaded with approximately 1 mg/cm^2 of mercuric-iodide. The data are quite similar to those observed with lead except that the K and L fluorescence of iodine is observed together with the L peak of mercury. The prominent peaking of L radiation of heavy elements observed in both the uncorrected and background corrected spectra indicates that this procedure can be used for monitoring air contaminations for even smaller amounts of metals in the samples. Accuracies of the order of one percent were obtained in one minute counting time. The observed separation of the fluorescence radiation of heavy elements from the peak of the scattered radiation indicates that the same analysis can be performed using a thin crystal, thin window scintillation spectrometer with the attendant increase in sensitivity.

FIG.38 - L X-RAY FLUORESCENT SPECTRA OF LEAD DUST ON FILTER PAPER.

FIG.39 X-RAY FLUORESCENT SPECTRA OF MERCURIC IODIDE ON FILTER PAPER.

A proportional counter with its better energy resolution would, however, be advantageous for the analysis of a heavy metal in the presence of a medium Z element, similar to the mercuric-iodide. Discrimination between elements of adjacent atomic number in the source sample seems to be limited with either type of detector. The use of higher energy x-ray source for excitation of K fluorescence is also expected to be of limited use in the analysis of a mixture of heavy elements since shielding and scattering problems will be increased.

C. Thickness Gaging

As discussed in Section II, the x-ray spectral distribution is an important parameter in thickness and density gaging since it determines both the total attenuation of x-ray flux and the rate of change of absorption with thickness. Thus, there exists an optimum choice of x-ray energy for each thickness of a given material such that the product of absorption coefficient and thickness leads to an optimum condition of readability.⁸ This can be defined as a ratio between the sensitivity S and the statistical fluctuation $\sqrt{I}$,

$$S = dI/(dt/t) \quad (36)$$

$$R = tdI/\sqrt{I} dt \quad (37)$$

The above relations are referred to ideal conditions of exponential absorption. This, however, is not realized in most practical situations. For reasonable thickness of absorber, scattering changes the energy distribution of the radiation as seen by the detector.

Where x-ray intensity can be varied over a wide range, optimum conditions can be obtained by adjusting x-ray flux and peak energy

until the desired combination of sensitivity and statistical variation of the signal is achieved. In those applications where the size or weight of an x-ray source is limited, however, a radioactive source of x-rays is an obvious answer. Beta excited x-ray sources represent a particularly attractive solution since their x-ray energy distribution can be varied accordingly to the choice of the target material and thickness.

Sources using the three beta emitters studied in this program have been tested in thickness gaging of lucite, aluminum and steel. These materials cover a range of atomic numbers for which gaging by x-ray absorption is indicated. Measurements were, of course, concerned with thicknesses of a few grams per cm² of materials, between the range covered by beta gaging and that covered by gamma gaging. Specifically, the 500 mc krypton source with cone targets, the 10 mc strontium-90 source (Section III) with sandwich targets, and 200 C promethium source were evaluated.

Several types of detectors and reading instrumentation were used in preliminary experiments during which we investigated both the source performance and the effect of detection scheme on the results. Attenuation of x-rays through an absorber was studied mainly with an ionization chamber and a thin plastic scintillator coupled to a photomultiplier. A thin NaI scintillation spectrometer was also used in pulse operation for the measurement of total x-ray intensity attenuation with a count-rate meter and in a study of x-ray peak attenuation with pulse height analysis. The results of these preliminary investigations show that the sensitivity of measurements depends to a certain extent on detector characteristics and mode of operation. We limit our report to the results obtained with an ionization chamber,

since it represents the great majority of detectors in use in industrial gaging applications, and a thin NaI detector coupled to a count rate meter.

The ionization chamber used was 5 inches in diameter and 4 inches long with a thin aluminum window and filled with P-10 gas. The diameter to source distance was three to six inches depending on the density of the absorber. Ionization current was measured with a Keithley type 410 electrometer.

Figures 40 through 44 show the transmission through varying thicknesses of lucite, aluminum and steel for different isotopic sources of secondary radiation and the two detector systems. For both aluminum and steel, the promethium source gives the highest sensitivity and readability as they have been previously defined. Lucite, however, is best measured by the krypton-zirconium source, although the differences between the sources are not large. Thus it follows, that the promethium-147 source should have wide applicability for gaging materials in the range of one to four gm/cm². The improvement in performance over cesium-137 for steel is illustrated in Fig. 45. These curves were normalized to the same zero absorber reading. It should be noted that the promethium-147 source gave an absolute current 5 times larger than the nominal 200 mc cesium-137 source used.

D. Radiography Using a Promethium-147 X-Ray Source

Radiographs of several metal objects were taken using the 200 curie promethium-147 source. The negatives are reproduced in Fig. 46. The x-ray intensity peaks at the K-line of promethium, approximately 38 Kev. Two types of radiographs were made: (1) the source was collimated using a 2 mm diameter aperture, see Fig. 47, and had a dose

FIG. 40 - RELATIVE X-RAY TRANSMISSION THROUGH LUCITE USING A NaI DETECTOR.

FIG. 41 - RELATIVE X-RAY TRANSMISSION THROUGH ALUMINUM USING A NaI DETECTOR.

FIG.42 - RELATIVE X-RAY TRANSMISSION THROUGH STEEL USING A NaI DETECTOR.

FIG.43 - RELATIVE X-RAY TRANSMISSION THROUGH ALUMINUM USING AN IONIZATION CHAMBER

FIG.44- RELATIVE X-RAY TRANSMISSION THROUGH STEEL USING AN IONIZATION CHAMBER

FIG.45- X-RAY ATTENUATION IN STEEL

A

B

FIG. 46 RADIOGRAPHS USING PM^{147}

A - 45 minute exposure, collimated

B - 4.5 minute exposure, uncollimated

SOURCE COLLIMATOR

FIG.47- RADIOGRAPHY APPARATUS

rate of approximately 10 mr/hr at one foot, (2) the source was uncollimated with an effective diameter of 7.2 mm with a dose rate of approximately 100 mr/hr at one foot. The film used was high speed Kodak No-Screen Medical X-Ray Film in cassettes of black paper and 0.0015 inch thick aluminum foil. Exposed films were developed for 8 minutes and fixed for 20 minutes in standard x-ray solutions.

The objects radiographed, Fig. 46, were (1) a 0.030 inch thick copper sheet with 0.015 inch, 1/32 inch, 1/16 inch, 1/8 inch, 3/16 inch and 1/4 inch diameter holes, (2) a stepped-wedge with 1, 3, 5 and 7 thicknesses of copper, each approximately 43.2 mg/cm^2 , (3) an aluminum alloy elbow connector with a 0.100 ± 0.025 inch thick mounting plate, and (4) a steel tube, wall thickness 0.005 inch, with a steel shim-stock liner approximately 0.0032 inch thick. Films A and B were made with the source six inches from the films with all objects in contact with the films except the drilled copper sheet which was 1/2 inch above the films. This separation emphasizes the definition obtainable with this source. Film A was made with the collimated source and a 45 minute exposure, while film B was made with a 4.5 minute exposure and the uncollimated source. Both exposures show two defects in the aluminum alloy casting, one an internal void and the other a surface depression. The thin line shown in the steel tube is due to overlapping and gapping of the shim-stock liner edges, a change of approximately 20 percent. The definition resulting from the two source diameters is shown by the sharpness of outline in the image of the holes in the drilled copper sheet. Contrast due to subject thickness is seen in the copper wedge image.

If one assumes a monochromatic photon source and a linear relationship between intensity and film density, and defines sensitivity as the ratio of the change in intensity to the fractional change of thickness, then, the optimum photon energy for maximum sensitivity about some thickness t of a given material is found by the following relationships:

$$S = dI/(dt/t) \quad (36)$$

or
$$S = -\mu I_0 e^{-\mu t} t \quad (38)$$

$$ds/dt = -\mu I_0 e^{-\mu t} (1 - \mu t) = 0 \quad (39)$$

$$\mu = 1/t \quad (40)$$

where

S = sensitivity

I = intensity

t = thickness of absorber

μ = x-ray attenuation coefficient for the given material.

The thickness of several metals for maximum radiographic sensitivity using 40 Kev x-rays are given in Table IX.

A series of experiments indicated that the penetration of the radiation from the promethium-147 source was greater than expected from 40 Kev x-rays. This is undoubtedly due to the high energy radiation which is integrated in the photographic process. A second set of radiographs was made to obtain a comparison between the beta excited x-ray source and a commercial x-ray unit. Figure 48 shows two radiographs of 0.094 in. of steel with two Air Force type penetrometers 0.012 in. and 0.007 in. thick plus a 0.002 in. foil penetrometer drilled to Navy Bureau of Ships specifications. 48 A is the radiograph resulting from a

Table IX

OPTIMUM THICKNESSES OF ABSORBERS FOR MAXIMUM
SENSITIVITY USING 40 KEV X-RAYS

Absorber	μ (cm ² /g)	t (g/cm ²)	t (mils)
Aluminum	0.558	1.79	~ 265
Iron	3.64	0.275	~ 14
Copper	4.83	0.207	~ 9

A

94 IN STEEL
6 IN 6 MIN

B

PENNIES INDUSTRIAL X-RAY CO
E 948 3
MCD 22 CHICAGO ILL 8

FIG. 48 COMPARATIVE RADIOGRAPHS

A. PM¹⁴⁷

B. Conventional X-Ray Machine

6 min. exposure with a source to film distance of 6 in. using type F film and Patterson high speed fluorescent screens. 48 B was obtained with a one minute exposure at 140 kvp, 5 ma and 40 in. source to film distance using type AA film: The tube utilized a tungsten target and a 2.5 mm focal spot. It should be again pointed out that the promethium source intensity can be increased by at least a factor of three over the value used to obtain these radiographs with a corresponding possible decrease in exposure time.

Any discussion of beta excited x-ray sources for radiography should include the use of image intensifiers which can greatly extend the range of such applications. The brightness increase obtainable through the use of intensifiers can greatly reduce the source intensities required with only a modest loss in image quality.

An image intensifier demagnifies the image electron-optically, permitting a resultant gain in brightness. Gains of 10^3 over fluorescent screens are commonly reported,^{16, 17} and some systems yield brightness gains up to 10^6 . A basic limitation, however, is the amount of light produced in the initial fluorescent screen per x-ray since the intensifier can only decrease the information content of the image created at the screen. Linden¹⁷ says, "-----once the image from the fluorescent screen has been intensified by a factor of 30-50, any further intensification can only serve to make the image brighter without making more information available to the radiologist." He goes on to point out that the only way to increase the available information is to increase the number of photons absorbed at the fluorescent screen.

In an effort to determine the practical improvement afforded by intensifiers, studies were made of typical objects using a

Phillips Eindhoven intensifier. Efforts to obtain photographs of the intensified image were unsuccessful and our comparisons must of necessity be somewhat qualitative. Examination of the same objects radiographed and shown in Fig. 46 enabled the following conclusions to be drawn:

1. The minimum hole size visible in the penetrometer was 1/16 inch diameter.
2. The step wedge showed as three steps, the two thickest sections being of equal optical intensity.
3. Neither the line in the steel tube nor the flaws in elbow connector were visible.

Subsequently we were able to briefly examine the performance of the source with an improved intensifier system.* Polaroid pictures taken of the viewing screen indicated that, although the brightness was marginal for direct viewing, there was sufficient x-ray flux to provide good information density. Skull photos and examination of wedges and penetrometers were used to evaluate performance. Further improvements are possible through increased source intensity, higher intensifier gains (this unit was operated at a gain of approximately 2000), and the use of beryllium windows on the intensifier tube. All of these improvements are within the present state of the art and it is our firm belief that a very satisfactory direct viewing system can be constructed which will be suitable for both medical and light industrial purposes.

At the same time that the image intensifier tests were being made, an experimental high speed Polaroid x-ray system being

* Made available through the courtesy of Picker X-Ray Company.

developed by Picker X-Ray Company was made available. The preliminary results were very encouraging and arrangements were made to obtain one of the first production models on loan. Figures 49 and 50 illustrate the two medical radiographs obtained with the promethium-147 source and the 3000 speed Picker-Polaroid system.

The complete portability of the isotopic source - Polaroid film combination is very exciting. No power is needed, no dark-room facilities are necessary, and no bulk chemicals or water supply are involved. Thus radiographs can now be taken anywhere, anytime with the results immediately available. This should have great advantage for military medical use as well as possibilities for rapid inspection of aircraft members to mention but a few of the many potential applications of a truly portable x-ray system.

FIG. 49 RADIOGRAPH USING PM^{147} POLAROID 3000 FILM

FIG. 50 RADIOGRAPH USING PM^{147} POLAROID 3000 FILM

REFERENCES

1. Liden, K., and Starfelt, N., Arkiv Fysik 7, 193 (1954).
2. Reiffel, L., Nucleonics 13, No. 3, 22 (1955); U. S. Patent 2,797,333.
3. Reiffel, L., and Humphreys, R. F., Proc. Int. Conf. (Geneva) Vol. 15, 291 (1956).
4. Kereiakes, J., and Krebs, A. T., Nucleonics 13, No. 4, 78 (1955).
5. Kereiakes, J., and Krebs, A. T., Paper 809, Geneva Conference (1958).
6. Leveque, P., Martinelli, P., and Chauvein, R., Proc. Int. Conf. (Geneva) Vol. 15, 142 (1956).
7. Muller, R., Reported at ACS Meeting, Chicago, Nov. (1958).
8. Nickerson, R. A., Nondestructive Testing, March-April (1958) p. 157.
9. Brownell, L. C., Coleman, C. W., Fox, C. J., and Nehemias, J. V., Report 2471-2-F, Dec. (1957).
10. Starfelt, N., Cederlund, J., and Liden, K., Jr. Appl. Rad. and Isotopes, 2, 265 (1957).
11. Evans, R. D., The Atomic Nucleus, McGraw Hill (1955).
12. Heitler, W., The Quantum Theory of Radiation, Oxford Univ. Press, (1944).
13. Burhop, H. L., Proc. Camb. Phil. Soc., 36, 43 (1940).
14. Powell, H. M., J. Chem. Soc., 298, 468 (1950).
15. Baumgartner, W. V., Nucleonics, 18, No. 8, 76 (1960).
16. Klein, M., Proc. of I.R.E., 47, May (1959).
17. Linden, B., Proc. of Sixth Scintillation Counter Symposium, Jan. (1958).
18. Note Added in Proof: The gamma branching ratio for krypton-85 was recently found to be high by approximately a factor of two. Rider, B., and Peterson, J. R., GEAP-3496.