2-
3-21-77

OAK RIDGE NATIONAL LABORATORY

OPERATED BY
UNION CARBIDE CORPORATION
N. J. 07030-5000

U.S. GOVERNMENT PRINTING OFFICE

ORNL/MIT-239

MASTER

DATE October 1, 1976 COPY NO

SUBJECT: Cellulose Acetobutyrate Films and Beryllium Oxide Discs for Low-Level Radiation Monitoring

Authors: S.A. Ventura, D.E. Kleinschmidt, and J.B. Mbu

Consultants: R.B. Gammage, J.H. Thorngate, and T.F. Gessell

ABSTRACT

The effect of mylar films on the attenuation of alpha particle energy and the production of etchable tracks in cellulose acetobutyrate was studied. A model developed predicts a 15- μ optimum mylar film thickness, while experimental results indicated a 22.8- μ optimum. The effect of alpha particle and potassium hydroxide solution interaction with CAB was reviewed and process improvements suggested. The TSEE response of BeO discs to tritium at 5.0 mCi/m² for up to 15-hr exposure was also investigated. An average TSEE/B ratio of 0.02 was obtained.

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

Oak Ridge Station
School of Chemical Engineering Practice
Massachusetts Institute of Technology

86
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

BLANK PAGE

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
Price: Printed Copy \$4.00; Microfiche \$3.00

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

Contents

	<u>Page</u>
1. Summary	4
2. Introduction	4
2.1 Background	4
2.2 Objectives and Method of Attack	5
2.3 Theory	5
2.3.1 Decay Chain for Radon and Tritium	5
2.3.2 Cellulose Acetobutyrate Detector	5
2.3.3 Mylar Thickness Optimization Model	11
2.3.4 Thermally Stimulated Exoelectrons from BeO	11
3. Apparatus and Procedure	11
3.1 Radon Exposure Chamber for CAB Experiments	11
3.2 Radon Calibration Procedure	15
3.3 Tritium Apparatus	15
3.4 Tritium Monitoring Procedures	19
3.5 TSEE Response	19
4. Experimental Results	19
5. Discussion of Results	21
6. Conclusions	23
7. Recommendations	23
8. Acknowledgment	23
9. Appendix	24
9.1 Radon-222 Activity Measured by Lucas Cell	24
9.2 Level of Exposure to Radon	24
9.3 Number of Tracks in CAB per Film Based on an Average Activity	24
9.4 Theoretical Evaluation of Optimum Mylar Thickness	25
9.5 Calculation of Incident Beta Particles on BeO Surface	25
9.6 Nomenclature	27
9.7 References	28

1. SUMMARY

Cellulose acetobutyrate (CAB) films were irradiated with alpha particles through a mylar attenuator. The thickness of the mylar was varied to produce the greatest number of damage tracks in the CAB. Damage tracks were enlarged in a KOH solution by an electrochemical etching method. A model predicted an optimum thickness 7 μ less than the experimental optimum of 22.8 μ . The optimum did not change when activity and exposure time to radon were varied at constant fluence; however, this did change the sensitivity of the CAB film. It is suggested that alpha irradiation of CAB preferentially breaks specific carbon-carbon bonds in the polymers. The KOH etchant then erodes the CAB in a manner analogous to cellulose erosion.

The TSEE response of BeO discs was determined from 1.50 to 15.25 hr at 5.0 mCi/m³ tritium concentration. The TSEE response increases linearly with exposure time. The TSEE per incident beta ratio is 0.02.

2. INTRODUCTION

2.1 Background

The Solid State Dosimetry group of the Health Physics Division of ORNL is currently evaluating several detection systems for monitoring low level radiation. Two of these methods are alpha particle track etching of cellulose acetate butyrate (CAB) films for radon monitoring and thermally stimulated exoelectron emission (TSEE) from beryllium oxide discs for tritium detection.

Alpha particle irradiation of CAB film results in tracks from bond breakage in the polymer. These tracks can be enlarged for convenient track counting with an electrochemical etching process. Previous work in the Health Physics Division has shown that etching of the CAB is most effective when the incident alpha particle energy is 0.5 to 4.0 Mev. Gessell(1) investigated the attenuation of 6.0 and 7.7 Mev alpha particles of radon decay with mylar film. He found no visible tracks with 5- and 14- μ -thick mylar films but observed a large number of tracks in the CAB with a 30- μ mylar film. He also observed an apparent change in the sensitivity [tracks/(pCi/l)-hr] of the film when radon concentration was varied but fluence held constant. Before field testing CAB dosimeters, it is necessary to determine the mylar thickness which will provide the maximum sensitivity and resolve the problem of sensitivity variation with concentration.

Irradiated BeO discs will emit exoelectrons from a thin surface region upon heating. This phenomenon, known as thermally stimulated exoelectron emission (TSEE) has been used in an alpha detector. It is hoped that the detection of the low energy (5 keV) tritium decay beta particles

at activity levels below the maximum permissible concentration (MPC) of 2.3 pCi/cm^3 will also be possible with TSEE.

2.2 Objectives and Method of Attack

The objectives were to: (1) determine the thickness of mylar which gives the greatest number of tracks in CAB for a given alpha fluence, (2) review proposed mechanisms of alpha particle interaction with the CAB film, (3) propose a mechanism for the interaction of the KOH etching solution with CAB film, and (4) determine the TSEE response of BeO discs to tritium decay at sub-MPC activity levels.

The optimum mylar thickness was first calculated using a simple model presented in Sect. 2.3. This model was also used to determine the range of mylar thickness for experiments. The CAB was first exposed to radon at a constant concentration and exposure time. The variation in the number of tracks produced was analyzed to obtain the optimum mylar thickness. With this optimum thickness, the CAB sensitivity variation was measured by exposing the polymer to the same fluence as in the previous experiments but at different activities or radon daughter concentrations.

BeO discs were exposed to a tritium/airmixture at one atm and an activity of 5 mCi/m^3 for 1.5 to 15 hr. Analysis of the TSEE response versus exposure time data assumed the response was a function of fluence only.

2.3 Theory

2.3.1 Decay Chain for Radon and Tritium

The radioactive decay of radon is shown in Fig. 1. Tritium decay produces a helium atom via emission of a 5 keV beta particle:

2.3.2 Cellulose Acetobutyrate Detector

Previous work by the Solid State Dosimetry Group at ORNL has indicated that the quantity and diameter of tracks produced in CAB film is related to the energy of the incident alpha particle. If the energy of the alpha particle is less than 0.5 MeV, no etchable tracks are produced.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
SCHOOL OF CHEMICAL ENGINEERING PRACTICE
AT
OAK RIDGE NATIONAL LABORATORY

Rn²²² DECAY PRODUCTS

DATE	DRAWN BY	FILE NO.	FIG.
9-28-76	SAV	CEPS-X-239	1

If the incident energy is between 0.5 and 4.0 MeV, the alpha particle will leave a track which can be electrochemically etched to produce microscopically countable tracks. For energies above 4 MeV, the particle does produce a track, but etching does not enlarge the track sufficiently so that it can be seen.

Katz (4) has suggested that the amount of damage depends on the rate of ionization or rate of energy transfer from the alpha particle to CAB electrons. Bohr (3) approximated the amount of energy transferred in terms of the energy of the particle, the charge, and the closest distance of approach, b , between the particle and an electron.

$$\Delta E = \frac{(\Delta P)^2}{2m} = \frac{(F\Delta t)^2}{2m} = \frac{(Fb)^2}{2mv^2} = \frac{Z^2 Q_a^2}{8m(\pi\epsilon vb)^2} = \frac{e^4}{8m(\pi\epsilon vb)^2} \quad (1)$$

The transfer of this energy to CAB electrons can result in

- excitation followed by de-excitation of the electrons through photon emission
- loss of the electrons or ion formation
- bond breakage with radical formation.

There is conflicting information as to which of these last two events is most probable for alpha interaction with polymers (7, 8).

The energy threshold for ion formation is taken as the first ionization potential for the group involved. The energy threshold for direct bond breakage is taken as the bond formation energy (Fig. 2).

For a 2-MeV incident alpha particle and a bond strength of 4 eV, solution of the Bohr equation shows that unless an alpha passes within $1 \times 10^{-2} \text{ \AA}$ of a bond, insufficient energy is transferred for bond breakage to occur. Therefore, it was assumed that an alpha particle does not interact with the electrons in more than one atom at a time and that based on the relative bond strengths, the net result of alpha interaction with CAB is breakage of the C₁-C₂, C₂-C₃, or C₃-C₄ bond. Since no electron is lost in bond breakage, it is assumed that a radical results at either termini of the broken bond. Rapid hydration of radicals (7) and the rearrangement of radicals to form double bonds (8) are reported in the literature. It was assumed that one of the two events occurred at each end of the broken bond.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
SCHOOL OF CHEMICAL ENGINEERING PRACTICE
AT
OAK RIDGE NATIONAL LABORATORY

CAB BOND ENERGIES AND IONIZATION POTENTIALS

DATE	DRAWN BY	FILE NO.	FIG.
9-24-76	DEK	CEPS-X-239	2

For bonds $C_1 - C_2$ or $C_3 - C_4$:

1.

↓

For the $C_2 - C_3$ bond:

2.

In case (1) the break leads to a double bond near an oxygen which will lead to chain scission upon treating with hydroxide as shown below:

The etchant will erode the CAB starting at the most electron deficient position (10, 11). A track will be enlarged to optical size by etching only if the etching rate along the track exceeds the surface etching rate (11). In the electrochemical etching process, the high voltage, high frequency AC field serves two purposes: it increases the mass transfer rate of etchant into the track and the joule heating associated with conduction serves to locally heat the fluid, thereby increasing the etching rate.

2.3.3 Mylar Thickness Optimization Model

The following model was used to approximate the mylar thickness that would attenuate alpha energies. In Fig. 3 a radon daughter is located at an arbitrary point on the mylar surface. It was assumed that alpha particles can be emitted at any angle from this origin and the particle path is straight. It was further assumed that the number of 5.9-MeV alphas and 7.7-MeV alphas emitted (Fig. 1) were equal. The minimum angle at which an alpha particle can penetrate the surface and still emerge from the mylar with an energy of less than 4 MeV is θ_1 . The maximum angle of alpha penetration such that it will emerge from the mylar with an energy greater than 0.5 MeV is defined as θ_2 . The fraction of emitted alphas which would register in the CAB is taken as the area between θ_1 and θ_2 on a sphere with a radius equal to the mylar thickness divided by the total area of the sphere. This fraction versus mylar thickness is plotted in Fig. 4.

2.3.4 Thermally Stimulated Exoelectrons from BeO

Very little is known about the surface phenomenon of TSEE. Low energy radiation interacts with BeO, filling defect centers in the solid with electrons (5). Upon heating, the defect centers lose the electrons. The electrons can leave the solid only if their energy is greater than the electron affinity of the BeO. This emission can be monitored with a G-M counter. The discs have been shown to be sensitive to surface cleanliness, degree of hydration, and thermal history (2).

3. APPARATUS AND PROCEDURE

3.1 Radon Exposure Chamber for CAB Experiments

The schematic diagram of the exposure chamber for the CAB experiments is illustrated in Fig. 5. It consists of a foam filter covering a wire mesh dome which is attached to a Plexiglas plate. The Plexiglas plate has aluminum foil on its surface and a threaded opening in the center. It is supported on a wooden base by three aluminum rods. A high voltage generator supplies 400 v DC to the dome. A silicon diode detector can be mounted in the Plexiglas base to be used as a calibrated detector for incident alpha particles. Signals emitted from the diode are amplified in an ORTEC 109A 47 mV preamplifier. The amplified pulse is fed into an ORTEC Model 455 single channel analyzer which records the pulses generated during an interval of time (100 sec). The analyzed pulse is fed into a Tennelec 500P scaler.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
SCHOOL OF CHEMICAL ENGINEERING PRACTICE
AT
OAK RIDGE NATIONAL LABORATORY

GEOMETRY FOR MYLAR OPTIMIZATION

DATE 9-24-76	DRAWN BY DEK	FILE NO. CEPS-X-239	FIG. 3
-----------------	-----------------	------------------------	-----------

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
SCHOOL OF CHEMICAL ENGINEERING PRACTICE
AT
OAK RIDGE NATIONAL LABORATORY

CAB FOIL EXPOSURE CHAMBER

DATE
9-24-76

DRAWN BY
DEK

FILE NO.
CEPS-X-239

FIG.
5

A 55-gal drum containing uranium for the radon gas source is pumped at a rate of approximately one liter/sec into a second drum where the hemispheric chamber is located. A fan is placed at the bottom of the second drum to circulate the radon gas. This apparatus is shown in Fig. 6.

A Lucas cell measures the activity level of radon. The Lucas cell is evacuated to 10 μ m Hg before a sample is taken. When sampling from high to low radon concentrations, precautions were taken to flush the valve sampler twice to insure correct countings in the gated decade scaler.

3.2 Radon Calibration Procedure

Radon gas was pumped from the first drum for 140 sec. The activity level of radon in the exposure vessel was then measured with the diode. After waiting for 5 min to allow the fan to mix the radon gas, alpha particles were counted. Initially readings were taken at 3-min intervals. Later, when a decrease in the rise of counts/100 sec was observed, readings were taken at 5, 10, and 20-min intervals. After 4 hr of operation, radon had essentially equilibrated with its daughters and a Lucas cell sample was taken.

Dome operating voltages of 100, 200, 300, 400, 500, 600, and 1000 volts and counts recorded from the diode for 40 min at each of these voltages indicated the least variation in counting rate occurred at 400 volts.

For the CAB experiment, the diode detector was replaced with a mylar-CAB disc. Eleven different thicknesses of mylar were used. After the alpha irradiation, the CAB films were etched. Etching took place in the cell diagrammed in Fig. 7. CAB foils were placed between two partitions. The etchant was a 28 wt % aqueous solution of KOH. The eleven samples were etched for four hours each at 1500 v, 400 Hertz, at room temperature.

3.3 Tritium Apparatus

Six Thermalox 995 ceramic BeO discs, each 12.7 mm in diameter and 1.6 mm thick, were exposed to tritium. A Triton gas monitor measured the concentration of tritium. Six glass exposure vessels and a tritium supply container were connected to the monitor forming a closed loop system. The glass vessels were wrapped in paper to prevent loss of sensitivity of the BeO discs when exposed to light.

The TSEE counter is shown in Fig. 8. The temperature programmer is connected to the GM counter stage. The TSEE response as a function of temperature is plotted on an x-y recorder.

3.4 Tritium Monitoring Procedures

Six BeO discs were exposed to a calibration standard cesium-137 for 34 sec at 3.76×10^7 pCi. The discs were then counted for TSEE response. The calibrated BeO discs were next exposed to tritium at an activity level of 5×10^{-3} Ci/m³ for up to 15 hr. The BeO discs on contact with tritium, dust particles, and foreign matter will exhibit a burst of electron emission which affects the radiation induced signal (2). Therefore, the BeO discs were washed in methanol after each tritium exposure for four minutes in a ultrasonic bath. After washing, they were dried in an oven at 100°C for one minute before counting.

3.5 TSEE Response

To obtain a plot of TSEE response versus temperature, the temperature programmer was adjusted at 2°/sec. TSEE response was recorded at temperatures between 225 and 450°C. After counting, the BeO disks were left to cool to a temperature of 250°C before removal from the G-M counter and placed on a brass plate to cool to room temperature.

4. EXPERIMENTAL RESULTS

Etched tracks as a function of mylar thickness are shown in Fig. 9. Experimental data have been normalized to an equivalent exposure of 19 hr at an activity level of 50 pCi/liter. The data are summarized in Table 1. The model for alpha interaction is based on the fraction of alpha

Table 1. Summary of CAB Results

Sample	Mylar Thickness (μ)	Radon Activity (pCi/liter)	Exposure (hr)
1	15.2	46.4	19
2	19.0	50.2	19
3	22.8	48.0	19
4	26.6	48.0	19
5	26.6	50.5	19
6	30.4	51.7	19
7	30.4	41.5	19
8	34.8	58.0	19
9	34.8	46.7	19
10	19.0	18.2	40
11	22.8	14.5	40

particles which will register in the CAB film and on the number of incident registrations from the diode experiment.

The results of the tritium experiments, TSEE response versus incident beta particles, and TSEE/ β ratio are represented in Table 2.

5. DISCUSSION OF RESULTS

As can be seen from Fig. 9, the optimum mylar thickness is 22.8 μ , a value somewhat greater than the model optimum of 15 μ . Sensitivity changed with activity level for a constant fluence, but insufficient data were obtained to determine a functionality. The alpha particle interaction with CAB film is probably localized at the C₁-C₂, C₂-C₃, or C₃-C₄ carbon bonds. It is suggested that the primary effect of irradiation is bond breakage. Breakage can lead directly to chain scission or can lead to an intermediate which will be attacked by the OH⁻ etchant.

KOH attacks CAB film with a mechanism similar to that for cellulose attack. The OH⁻ group, a nucleophilic reagent, is an anion which attacks a position of lowest electron availability (12). For a given nucleophilic reagent, nucleophilicity is fairly well correlated with basicity. The order of nucleophilicity follows (12):

The reactivity of nucleophilic reagents has been tabulated by Swan and Scott (13). Based on their analyses, the order of nucleophilicity is

Nucleophilic displacements are characterized by unimolecular substitutions SN₁ and bimolecular reactions SN₂. In SN₁ the rate of reaction is independent of the anion; the entering group has no effect on the rate of SN₁ displacement. In SN₂ the rate of reaction depends on the nature and concentration of the anion; the more strongly nucleophilic the reagent the more favorably the reaction will be promoted (14).

The nucleophilic attack by an anion on the carbon causes steric hindrance. Steric effects which lead to the electron redistribution become appreciable only when the reacting particles are in close proximity (13). Low steric hindrance favors nucleophilic attack.

Table 2. TSEE Response at 5.0 mCi/m³ Tritium

<u>Exposure (hr)</u>	<u>TSEE ($\pm 2\%$)</u>	<u>Background</u>	<u>Net TSEE</u>	<u>Incident β¹</u>	<u>TSEE/β</u>
1.50	802	294	508	1.24×10^5	6.4×10^{-3}
1.75	4993	1920	3073	1.45×10^5	3.4×10^{-2}
2.00	5091	214	4877	1.65×10^5	3.1×10^{-2}
2.25	1858	213	1645	1.86×10^5	9.9×10^{-3}
3.00	4334	254	4080	2.48×10^5	1.7×10^{-2}
3.00	5258	284	4974	2.48×10^5	2.1×10^{-2}
15.25	39,641	215	39,426	1.26×10^6	3.1×10^{-2}
				Average	2.1×10^{-2}

¹See Appendix 9.5.

Size is also important in mass transfer since the surface etch rate must be less than the track etch rate for maximum etching efficiency. Taking into consideration nucleophilicity, steric effects and size of the entering group, the most efficient nucleophilic reagents as etch parameters should be $\text{CN}^- > \text{SH}^- > \text{OH}^-$. Therefore, potassium cyanide should be tried as an etchant instead of potassium hydroxide.

Substituents which withdraw electrons more efficiently from the cellulose ring, weakening the carbon bonds, should lead to a film more sensitive to alpha radiation. Substituents should increase the sensitivity to both alpha particle radiation and the etchant. Electronegative groups such as NO_3^- may fulfill this function. In the cellulose configuration the nitrate group would be chemically bonded to C₂, C₃, and C₆.

TSEE apparently increases linearly with activity for constant exposure time. Lack of data for mid-range activity levels leave some doubt about this linear approximation. The TSEE count per incident α on the BeO disc, 0.02, is lower than the previously reported value of 0.23 (2).

6. CONCLUSIONS

1. Irradiation of CAB film through 22.8 μ of mylar produces the maximum number of tracks per unit of area.
2. At constant fluence, the sensitivity of CAB film is higher at lower radon activity levels.
3. TSEE response of BeO disks is a factor of 10 lower than those obtained by Gammage (2).

7. RECOMMENDATIONS

1. The sensitivity variation of CAB film should be investigated to determine whether exposure time or level of activity is the important parameter. The work of Katz (4) suggests the latter is more important.
2. The effect of CN^- as an important etchant should be investigated experimentally.

8. ACKNOWLEDGMENT

We would like to gratefully acknowledge the assistance of R.B. Gammage, J.H. Thorngate, and T.F. Gessell.

9. APPENDIX

9.1 Radon-222 Activity Measured by Lucas Cell

A Lucas chamber monitors the activity level of radon. It records alpha counts/min. The volume of the chamber is 0.095 liters. The activity level of radon-222 in pCi/liter is determined by:

$$A = \left[\frac{\text{alpha counts/min}}{\text{Lucas eff}(\text{vol of chamber})} \right] \left[\frac{1 \text{ radon dis}}{2 \text{ particles}} \right] \left[\frac{1 \text{ min}}{60 \text{ sec}} \right] \left[\frac{100 \text{ pCi}}{3.7 \text{ dis/sec}} \right]$$

The Lucas cell efficiency is 88.5%. For 20 counts/min,

$$A = \left[\frac{20}{(0.885)(0.0956)} \right] \left[\frac{1}{2} \right] \left[\frac{1}{60} \right] \left[\frac{100}{3.7} \right] = 53.6 \text{ pCi/liter}$$

9.2 Level of Exposure to Radon

The exposure to radon at a given activity level is defined as (15):

$$E_2 = \int_0^t A_0 e^{-\lambda t} dt = A_0 \frac{1}{\lambda} (1 - e^{-\lambda t})$$

For example, at 50 pCi/liter and 19 hr of exposure,

$$\begin{aligned} E_2 &= 50 \text{ pCi/liter} \left[\frac{1}{2.5 \times 10^{-4} \text{ sec}^{-1}} \right] [1 - e^{-2.094 \times 10^{-6} \text{ sec}^{-1} \times 19(3600)}] \\ &= 2.66 \times 10^4 \text{ pCi-sec/liter} \end{aligned}$$

9.3 Number of Tracks in CAB Per Film Based on an Average Activity

The number of tracks per unit of area of sample 1 at a measured activity of 50.5 pCi/liter was 2509 per film. Based on the average activity of 50 pCi/liter for 19 hr, the normalized number of tracks per film, D, will be

$$D = \frac{50 \text{ pCi/liter}}{50.5 \text{ pCi/liter}}(2509) = 2484 \text{ tracks/film}$$

for normalized activity level of 50 pCi/liter.

9.4 Theoretical Evaluation of Optimum Mylar Thickness

The range of alpha particle energies for CAB track registration is 0.5 - 4 MeV. In the coordinate system of Fig. 3 we define θ_1 as the minimum angle that an alpha particle can emerge from the absorber mylar with an energy less than or equal to 4 MeV. θ_2 is the maximum angle that an alpha particle can emerge from mylar with an energy greater than 0.5 MeV.

The number of particles registering in the film is proportional to the solid angle between θ_1 and θ_2 . These angles are related by the thickness of the film and the stopping power of the mylar.

$\cos \theta_1 = \frac{T}{A}$	<u>A</u>	<u>B</u>	<u>Initial Energy</u>
	15	34	5.9
$\cos \theta_2 = \frac{T}{B}$	33	49	7.7

where A is the thickness of mylar that will decrease the 7.7 and 5.9 MeV particles to 4.0 and 0.5 MeV, respectively, (Fig. 10) and B is the stopping thickness. Thus, there is a solid angle for each energy particle, and in this case the angles overlap between 33 and 34 μ of mylar.

9.5 Calculation of Incident Beta Particles on BeO Surface

The activity for all experiments was 5.0 mCi/m³. Thus,

$$(5 \times 10^{-3} \text{ Ci/m}^3)(3.7 \times 10^{10} \text{ B/Ci-sec}) = 1.85 \times 10^8 \text{ B/m}^3\text{-sec}$$

Since the penetration range of B in air is ~0.1 cm, only β 0.1 cm above the disc were assumed to reach the surface. The volume of the BeO container was $7.16 \times 10^{-5} \text{ m}^3$. The volume of a spherical shell of this radius and 0.1 cm thick is $8.45 \times 10^{-6} \text{ m}^3$. Therefore, the number of betas that could reach the surface is,

$$(1.85 \times 10^8 \text{ B/m}^3\text{-sec})(8.45 \times 10^{-6} \text{ m}^3) = 1.56 \times 10^3 \text{ B/sec}$$

The ratio of BeO disc surface area to the spherical shell area provides a proportionality factor for calculating the fraction of betas that strike the disc.

$$\begin{aligned} & (1.56 \times 10^3 \text{ B/sec})(\text{area BeO disc/area of sphere}) \\ & = (1.56 \times 10^3 \text{ B/sec})\left(\frac{1.23 \times 10^{-4}}{8.34 \times 10^{-3}}\right) = 23.0 \text{ B/sec} \end{aligned}$$

The total incident beta radiation is then obtained by multiplying this factor by the exposure time.

9.6 Nomenclature

A	activity, pCi/liter at time t
A ₀	initial activity, pCi/liter
D	distance, meters
e	electron charge, 1.6×10^{-19} coulombs
E _L	exposure level, pCi-sec/liter
m	mass of helium nucleus, 6.68×10^{-27} kg
ΔP	momentum of particle
Q _α	alpha charge
Q _e	electron charge, e
t	time, sec
T	mylar thickness, μ
λ	radon decay constant, sec ⁻¹
θ ₁	angle of alpha particles on mylar, degrees
θ ₂	angle of alpha particle on mylar, degrees

9.7 References

1. Gessell, T.F., unpublished report of summer work at S.S. group, Health Physics Division, ORNL (1976).
2. Gammage, R.B., and J.S. Cheka, "Measuring Tritium with Exoelectron Dosimeters," Nuc. Inst. Methods, 127, 279 (1975).
3. Turner, J.E., "Calculation of Stopping Power of a Heavy Charged Particle in Matter," Health Physics, 13, 1256 (1967).
4. Katz, R., and E.J. Kobetich, "Formation of Etchable Tracks in Dielectrics," Phys. Rev., 170(2), 401 (1967).
5. Scharmann, A., "Exoelectron Emission, Phenomena and Parameters," 4th Int. Symp. on Exoelectron Emission and Dosimetry, Czech. Acad. Sci. and AEC, 12-26 (1972).
6. Fleischer, R.L., P.B. Price, and R.M. Walker, "Ion Explosion Spike Mechanism for Formation of Charged Particle Tracks in Solids," J. Appl. Phys., 36(11), 3645 (1968).
7. Chapiro, A., "Irradiation of Polymers," p. 22, Wiley, New York (1962).
8. Ormero, M., "Formation of Free Radicals in Polymers," p. 115, Plenum Press, New York (1970).
9. Bikales, N.M., and L. Segal, "Cellulose and Cellulose Derivatives," Part V, pp. 937-975, Wiley, New York (1965).
10. Machell, G., G.N. Richards, and H.H. Septon, "The Alkaline Degradation of Cellulose," Chem. Ind., 467 (April 13, 1975).
11. Gross, W.G., "Flux Measurements with Damage Track Detection," Atomic Comm. Canada, 5, 3 (1970).
12. Fieser, F.L., and M. Fieser, "Advanced Organic Chemistry," p. 319, Reinhold Publishing, New York (1961).
13. Hyne, T., "Physical Organic Chemistry," p. 161, McGraw-Hill, New York (1962).
14. Skies, P., "A Guidebook to Mechanism in Organic Chemistry," p. 25, Wiley, New York (1961).
15. Gammage, R.B., G.D. Kerr, and L. Huskey, "Exploratory Study of the Use of TSEE Dosimeters in Radon Monitoring," Health Physics, 30, 145 (1975).
16. Ouseph, P.J., "Introduction to Nuclear Radiation Detectors," pp. 1-189, Plenum Press, New York (1975).