Hazard Evaluation of Pm-147 Activated Self-Luminous Devices Made With "3M" Brand Radiating Microspheres

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APPLIED RESEARCH DEPARTMENT

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HAZARD EVALUATION OF SELF-LUMINOUS DEVICES MADE WITH "3M" BRAND RADIATING MICROSPHERES

Evaluation of the radiation safety aspects of any device containing radioactive material is usually divided into two hazard areas -- external and internal. Each of these will be considered in detail for 3M Brand Pm-147 Activated Self-Luminous Devices. Information on the composition and properties of some typical devices is given in Appendix 1.

Most applications of these self-luminous sources will be in the 5-50 microlambert brightness range. To achieve this brightness a Pm-147 specific activity of about 0.3 mc/cm^2 is needed for the 5 microlambert source and 3 mc/cm^2 for the brighter source. In discussing the safety aspects, an intermediate source with an activity of 1 mc/cm^2 will usually be considered.

I. External Hazard

1. Bremsstrahlung radiation

Since Pm-147 is a weak beta emitter, there is no whole-body radiation hazard from low level (millicurie) sources. The slight amount of bremsstrahlung produced is reduced to a low level by plastic shielding (Appendix 2). It must be emphasized, however, that the existence of this secondary radiation puts a practical limit on the extent to which surface dose can be reduced in self-luminous devices. It would seem reasonable to set limits of 5 mr/hr at the surface of the device and 1 mr/hr at 3" -- and further stipulate that the radiation contributing to this surface dose should consist of at least 90% soft x-rays of less than 100 KEV. This would assure that the surface radiation contains very little hard gamma components.

The radiation dose from the trace amount of gamma-emitting impurities in the Pm-147 is much less than that produced by the bremsstrahlung radiation (Appendix 2).

It is of interest to note that the dose of soft x-rays ($\sim$30 KEV) required to just produce a perceptible change in the skin is of the order of 300 roentgens delivered in one sitting[2]. Thus it is obvious that 3M Brand Pm-147 activated sources pose no hazard in this respect.

The only other major consideration from the external standpoint is the genetic hazard. All conceivable uses of self-luminous devices will not bring the device within more than a few inches of the gonads. In addition, shielding by clothing is quite appreciable over this portion of the body. It seems reasonable to state that the genetic hazard is less than that from normal background radiation.

To further emphasize the conclusion that 3M Brand Pm-147 activated self-luminous sources present no external hazard from secondary radiation, a comment by C. L. Dunham, M.D., Director of the AEC Division of Biology and Medicine, is worth noting[3].

"Earlier work by Lorenz and associates and recent work in this country and in England with continuous exposure at dose rates of a few tens of r down to 1 r or less per week have shown either a lesser effect, or in some instances no apparent effect, in terms of curtailment of average life span, leukemia or tumor induction, as the case might be, when compared with the effect of comparable total doses at relatively high dose rates. The findings at these dose rates (2 r per week is roughly one thousand times that incurred from natural or background radiation) suggest that there may indeed be from a practical standpoint a threshold for some of these effects or that at the worst the effect is very greatly reduced. Perhaps this results from repair of the damage by metabolic or proliferative activity of the cells."

It is also of interest to point out the rather surprising results obtained recently by Carlson and Jackson[1] in their study on the effect of low doses (0.28 to 3.9 rep/day) of ionizing radiation on mice. They found that the life span was actually increased up to a dose rate of 2.6 rep/day (Appendix 2). Much more work, of course, must be done in this area of low dose rates before any definite conclusions can be drawn.

2. Beta radiation and skin dose

There is no beta hazard from 3M Brand Pm-147 shielded sources since the maximum range of a Pm-147 beta particle is only 50 mg/cm^2 (0.02" in plastic). However, since some components of a self-luminous device must be handled in assembling the device, it is important to establish the beta dose to the hands in such an operation.

It has been well established[4] that there is no external dose hazard from alpha emitters. In fact alpha particles of energy 7 MEV and beta rays with an energy of 0.07 MEV will just penetrate the minimum thickness (7 mg/cm^2) of the protective epidermal layer of skin that surrounds the body. Since the average energy of the Pm-147 betas is 0.07 MEV only a small fraction (about 10%) of the beta energy will reach the basal layer of the epidermis. The limits of interest are 1) "permissible" surface dose -- 1.5 rep/week at the basal layer of the epidermis (Federal Register) or 15 rep/week of Pm-147 beta radiation (assuming 10% penetration of epidermal layer); and 2) "emergency" dose or that dose which, if delivered in a short time (hours), would just produce a discernable reddening of the skin -- about 10,000 reps for Pm-147 betas. (See Appendix 3 for details on both of these limits.)

An assembled Pm-147 source with 1/16" of plastic shielding has no surface beta particles and the radiation is almost completely secondary x-rays. This dose rate is always quite low as was pointed out in the preceding section, and it can be stated quite emphatically that there is no skin dose hazard from these assembled Pm-147 sources.

The next consideration is the dose to the hands to be expected when the self-luminous components are being assembled in a device. Calculation of dose rates from various shapes of beta sources have been made by many workers, but as Hine and Brownell[5] point out, "The dose rate at the surface of a β-ray applicator can only be measured. Owing to the complexities of β-ray absorption and scattering, it is not possible to calculate the dose rate reliably from the source strength."

Therefore, the surface dose rate of unshielded Pm-147 self-luminous sources was measured with a "Cutie Pie" ionization chamber. This instrument, with a window thickness of 7 mg/cm^2, has been shown to give a reasonable value for the beta dose at the basal layer of the epidermis[15]. The results are tabulated in Tables I,

III and IV, Appendix 3. If the case of a watch dial containing 1.0 mc of activity is considered, it is found that the dose rate delivered to the basal layer of the epidermis when in direct contact with the watch dial is 750 mr/hr (Table III, Appendix 3). Such a source could be handled for about two hours a week without exceeding the permissible level of 1.5 r/week at the basal layer of the epidermis. With surgical rubber gloves, the surface beta dose rate is reduced to 7 mr/hr, and the unshielded dial could then be handled continuously without exceeding the permissible level of 1.5 r/week.

To reach the minimum dose of 10,000 r for production of reddening of the skin, the dial would have to remain in direct contact with the skin for at least 18,000 hours or 750 days.

The facts seem to warrant the conclusion that there is no external danger to the skin from unshielded components of 3M Brand self-luminous devices -- either to the person assembling the device or to the user who accidentally or by design breaks the device apart.

3. Effect on the eyes

The lens of the eye may be changed after a rather large dose of penetrating radiation with the subsequent development of cataracts. With Pm-147 self-luminous sources, two types of radiation must be considered -- beta and bremsstrahlung.

Since the maximum range of the beta particle from Pm-147 (50 mg/cm^2) is less than the thickness of the protective layer of moisture and tissue over the lens of the eye, there is no danger from the betas. The distance from the surface of the eye through the conjunctiva, cornea, and anterior aqueous chamber to the lens is approximately 3mm (300 mg/cm^2).

Cataracts from occupational exposure to X-rays have not been recorded but those caused by clinical use have been studied. The minimum single dose of X-rays that resulted in the formation of a cataract was 200 r[4]. The cataracts were observed 20 years after exposure. Patients who received 175 r or less did not develop cataracts. With radiation treatment scheduled over a three-month period, the lowest dose associated with cataract formation was 550 r.

The amount and energy of the bremsstrahlung generated by the Pm-147 beta particles is a function of the absorbing material.

The dose is an extremely small fraction of the total surface dose and usually ranges from 1 to 5 mr/hr, depending on the amount of Pm-147 in the source. The peak energy usually ranges from 20 to 40 Kev.

If we assume the worst possible case -- direct contact of an unshielded Pm-147 activated source on the surface of the eye for 24 hours a day, it would take at least 35,000 hours or about 4 years to reach the minimum level for cataract formation of 175 r.

It is quite apparent that there is no danger to the lens of the eye from 3M Brand Pm-147 activated self-luminous sources.

II. Internal Hazard

1. Ingestion

The most serious potential health hazard problem encountered with low level (1-[illegible] millicuries) radioactive sources is the danger of ingestion. The radioactive material enters the body metabolism and is deposited to a greater or lesser degree in the bones or a vital organ. Radioactive isotopes which are liable to deposit in the bone tissue are Sr-90, Y-91, Zr-95, Nb-95, Ba-140, La-140, Ce-144, Pr-143, Pm-147, Pa-231, Th-239, Np-239, Pu-239, Am-241, and Cm-242. The 3M approach to this problem has been to render the isotope chemically and physically inert by incorporating it in "3M" Brand Radiating Microspheres. All isotopes now are "metabollically" inert. The inertness of these microspheres is shown by the leach data and the animal feeding results in Appendix 4. Briefly, these data show that only a few parts per million of the isotope are leached out in 7-day soak tests in such liquids as 1% Versene and 0.01N HCl. The latter is approximately the same pH as the stomach fluid. Further, Sr-90 microspheres fed to rats left no detectable activity in the body. (The limit of detection was less than .0007%.) Therefore, the level for ingestion of radioisotopes contained in 3M microspheres is many thousand-fold greater than the "permissible" level for uncontained radioisotopes. As an example, if we assume the same conditions to exist in man as in the rat, one could ingest at least 280 millicuries of Sr-90 microspheres before exceeding the 2 μc body burden. Feeding studies with Pm-147 carrier are underway.

Thus, the only hazard encountered with 3M carrier material, when ingested, would be the radiation damage to the gastro-intestinal tract as the material passed through the body, in the case of beta-emitting isotopes, and the whole-body radiation dose for gamma-emitting isotopes. Appendix 5 reviews the method of calculating the magnitude of these doses and presents a discussion of the possible hazards involved when "3M" Brand Radiating Microspheres are ingested. In the case of Pm-147, it is found that at least 30 mc would have to be ingested to approach a hazardous amount. Actually, because of the low energy of the Pm-147 beta, this limit is many-fold higher.

It should be pointed out that we are not considering a "permissible" limit for ingestion in the same sense that we consider a "permissible" limit to the hands. Ingestion can

hardly be considered a routine hazard. We have presented data on the possible hazard, however, to demonstrate that ingestion of sources made with 3M's ceramic microspheres would not be likely to produce injury of a permanent nature.

2. Inhalation

In order to be an inhalation hazard, the radioactive material must be dispersed in the air in a finely divided state. With self-luminous sources, this is most likely to occur as the result of a fire sufficiently hot to combust the organic binder holding the radioactive material and ZnS phosphor to the surface of the device. With 3M Brand self-luminous devices such an accident might release the Pm-147 microspheres from the surface and the question thus resolves to one of determining whether the free microspheres present an inhalation hazard.

Inhalation hazards do not exist if the material is too large to enter the respiratory tract. To be of any significance, most of the radioactivity must be on or in particles of 10 micron "aerodynamic" size or smaller[6]. Since the minimum size of 3M Brand Radiating Microspheres is 40 microns, it is apparent that they present no inhalation hazard.

III. Appendices

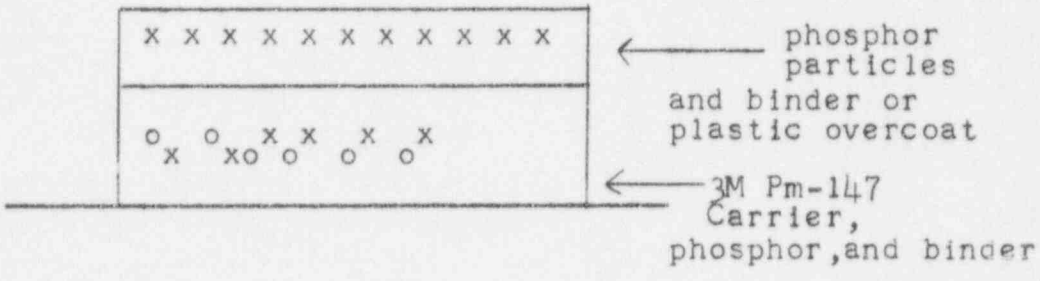
Appendix 1: Composition and Properties of Pm-147 Activated Self-Luminous Devices Made With "3M" Brand Radiating Microspheres

a) Description

The basic components in our material are:

1) "3M" Brand Radiating Microspheres containing Pm-147,
2) phosphor (ZnS), and
3) plastic binder.

This constitutes the radioluminescent slurry for preparation of the markers. The slurry is applied to the device by some appropriate technique such as screening, painting, etc. To increase the brightness level and reduce the surface radiation dose, a layer of phosphor and binder is sometimes applied as an overcoat. Another technique of reducing the surface dose is to apply a thin layer of plastic by spraying, dipping or painting.



This forms a tough, tenacious film which can withstand extremely rough treatment.

To reduce the radiation level at the surface of the device, a 1/16 inch thickness of plastic (or equivalent) is placed over the self-luminous area in the assembled device. For a source of 1 mc/cm^2, this surface dose can be reduced to 1 mr/hr. Of course, as the level of radioactive material is increased, the surface dose will increase somewhat.

b) Resistance to Leakage of Radioactivity

As pointed out in the preceding description, the Pm-147 is permanently incorporated into ceramic microspheres which are

then used to fabricate the final product. Wipe tests of fabricated self-luminous sources have never revealed any detectable leakage of radioactivity.

The carrier material itself is subjected to a soak test consisting of exposure of about 0.1 mc of Pm-147 labelled microspheres to 100 ml. of the solvent at 50° C. for up to 50 days. Under these conditions, typical values of isotope removal from the carrier are:

Solution	Temperature	Time	Pm-147 Removed
0.01 N HCl	50° C.	1 day	0.001%
0.01 N HCl	50° C.	7 days	0.002
0.01 N HCl	50° C.	50 days	0.02
1% Versene	50° C.	1 day	0.01
1% Versene	50° C.	7 days	0.02
1% Versene	50° C.	50 days	0.2

The following results indicate the general property of the microspheres in retaining a great variety of radioactive isotopes.

Isotope	% Removed (0.01 N HCl, 7 days at 50° C.)
Sr-90	0.001
Tl-204	0.0004
Pm-147	0.002
Co-60	0.001
Zr-65	0.003
Ag-110	0.0006
Fe-59	Not detectable
Na-22	0.002
Ra-226	0.002
Ca-45	0.015
Cs-137	0.004
Po-210	0.002

When the radioactive microspheres are incorporated into a weather-resistant structure, the product is that much more resistant to removal of activity. Typical constructions containing Pm-147 were subjected to water and 5% NaCl solutions for 14 days and showed no detectable activity in the solutions (lower detection limit was 1 ppm. or 0.0001% removal of isotope).

c) Radiation Stability

Ceramic Carrier

The ceramic microspheres containing the isotope have been subjected to a dose of 1000 megarads of 1 MEV electron radiation with no visible change nor any lessening of the ability of the carrier to retain the isotope in soak tests.

Plastic

Films of this plastic binder were not seriously affected by radiation at doses of 10-30 megarads, but tended to become brittle at doses over 100 megarads.

The plastic cases are made of methyl methacrylate which is the standard plastic used in the industry. The only effect of radiation below 100 megarads is a slight darkening which is almost negligible at the relatively low dose rates encountered in the 3M devices.

d) Brightness Decay

It has been found that the phosphor used in our products is extremely resistant to beta radiation. The tests were performed with a 1 MEV electron beam resonant transformer with a dose rate of 400,000 reps/second. Available data indicate that the brightness decay will parallel the isotope decay (Pm-147 has 2.6 yr. half-life). Thus, a unit, with initial brightness of 65 microlamberts will have a 32 microlambert brightness after 2.6 years.

e) Weathering

Accelerated Weather-O-Meter testing indicates that the lucite facing is the limiting material with regard to durability, and its life is normally at least 10 years. Outdoor exposure life should, therefore, exceed the useful life of the isotope.

Appendix 2: Bremsstrahlung Radiation

The main source of penetrating radiation (gamma or x-rays) in self-luminous sources is either bremsstrahlung or γ-emitting impurities in the Pm-147. A study was conducted in the 3M Research Laboratory to determine what fraction of this radiation was due to bremsstrahlung. Measurements were made by pulse height analysis with a Baird-Atomic single channel pulse height analyzer with a sodium iodide-thallium activated crystal and a Dumont 6292 Photomultiplier tube.

As a first experiment the bremsstrahlung from a 1 mc Pm-147 source in H_2O was compared with that from a 1 mc source of C-14 urea. The results (Figure 1) show that both sources have a peak at about 20 KEV.

The ratio of energy loss by bremsstrahlung to that by ionization is $\frac{E \cdot Z}{800}$, where E is the maximum energy of the beta particle in MEV and Z is the atomic number of the matrix in which the betas are absorbed.[8] Using this formula, one calculates that approximately twice as much bremsstrahlung energy is expected from a Pm-147 as from a C-14 source. In Figure 1, the ratio at peak energy is actually about 1:2.7, in fair agreement with the calculated value considering that the isotopes were not in the same medium.

As a method of equating the high energy components in ORNL-produced Pm-147, a 1 mc source was compared by integral PHA to a 10^{-5} mc Cs-137 source. The counts/minute above a base line of 0.240 MEV (just above the cutoff point on Pm-147 bremsstrahlung) were equal for the two sources (4000 c/m). Therefore, it is reasonable to assume that the Pm-147 contains less than 0.001% high energy gamma emitters ($\gamma > 0.240$ MEV). A calculation of the energy output of a 10^{-5} mc Cs-137 source shows that this quantity would emit 0.013 ergs/hr or about 0.13 mr/hr.

The penetrating radiation from a plastic shielded Pm-147 source was also established by PHA. The sample was a 15 mc source with a 3/32" plexiglas shield over the active area. As expected, (Figure 2) there was a shift in peak energy of bremsstrahlung emission to about 36 KEV, due to the higher atomic number material surrounding the source (ceramic carrier).

Using the tables of X-radiation absorption in Glasser[9] and converting the values (aluminum to plexiglas), the percent transmission of a 36 KEV x-ray through various thicknesses of plexiglas

was obtained. One finds 12% transmission through 1/16" plexiglas, 5% through 1/8" and 2.5% through 1/4". This was experimentally checked with a 3M source and found to hold (Table I, Appendix 3). The surface dose of the source, which was 0.5 mr/hr with a 1/16" plastic shield, was reduced to 0.3 mr/hr by the addition of another 1/16" sheet of plastic.

By calculating the total radiation dose of a 1 mc Pm-147 source using the formula in Friedlander and Kennedy[8], one can estimate the shielding required to reduce the surface dose to 1.5 mr/hr. The total bremsstrahlung energy output of a disk source 1" in diameter containing 1 mc Pm-147 is:

$$1 \text{ mc} \times 0.07 \text{ MEV/dis.} \times \frac{0.07 \times 40}{800} \times 10^{6} \frac{\text{ev}}{\text{MEV}} \times 1.6 \times 10^{-12}$$

$$\text{ergs/ev.} \times 2.2 \times 10^{9} \text{ dis/min/mc} \times 60 \frac{\text{min.}}{\text{hr}} = 52 \text{ ergs/hr/mc}$$

We are assuming an average atomic number of 40 for this calculation since the atoms in the ceramic carrier and the inorganic phosphor are the principal contributors to the bremsstrahlung. Note that this gives us the maximum energy output. Actually much of the Pm-147 beta energy is expended in the plastic shield over the source and results in a lower bremsstrahlung output. No consideration has been given here to internal bremsstrahlung since it makes only a minor contribution to the total dose.[10]

To convert this energy output to a dose rate reading we apply: (1) a 90% correction for self-absorption of 36 KEV x-rays (the unshielded sources are approximately equivalent to 0.5 mm of Al); and (2) a 90% correction for geometry. Thus the maximum bremsstrahlung energy output expressed in terms of dose of an unshielded self-luminous source containing 1 mc of Pm-147 labelled "3M" Brand Radiating Microspheres is:

$$52 \text{ ergs/hr/mc} \times 1/10 \times 1/10 = 0.52 \text{ ergs/hr/mc} \simeq 5.2 \text{ mr/hr/mc}$$

The addition of a 1/16" plastic shield would reduce this value to about 0.5 mr/hr/mc. This value is in fair agreement with our experimentally measured values as listed in Table I, Appendix 3.

Recent experiments by Carlson and Jackson[1] on the effect of low doses of ionizing radiation on mice showed that the life span was actually increased. Groups of rats were exposed to 0.28, 0.60, 2.57, and 3.96 rep/day for a 16-hour day during the irradiation period, which lasted from 4 months of age to 16 months

of age. A Co-60 source was used. The days of age at which 50% were dead for 0.28 r/day was 493; for 0.60 r/day, it was 510; for 2.57 r/day, it was 650; and for 3.93 r/day, it was 590. The average life span for the unirradiated controls was 445 days. It has been suggested that the mild doses of irradiation may be beneficial in stimulating renovation processes.

No attempt has been made in this report to convert all radiation dose values to the commonly accepted unit -- the rad. The primary reason for not doing so is that for Pm-147 bremsstrahlung radiation adsorbed in tissue, the value for the rad is approximately 75% of the roentgen reading. This figure was obtained from a report by Check and Linnenbom[11] who give equations and tabular data for calculating the adsorbed dose in rads when the composition of the material in the radiation field and the photonenergy are known. Using the "standard man" composition of 65% oxygen, 18% carbon, 10% hydrogen and 3% nitrogen and an average photon energy of 30 Kev for the Pm-147 bremsstrahlung one obtains a rads/roentgen ratio of 0.74.

FIG. 1

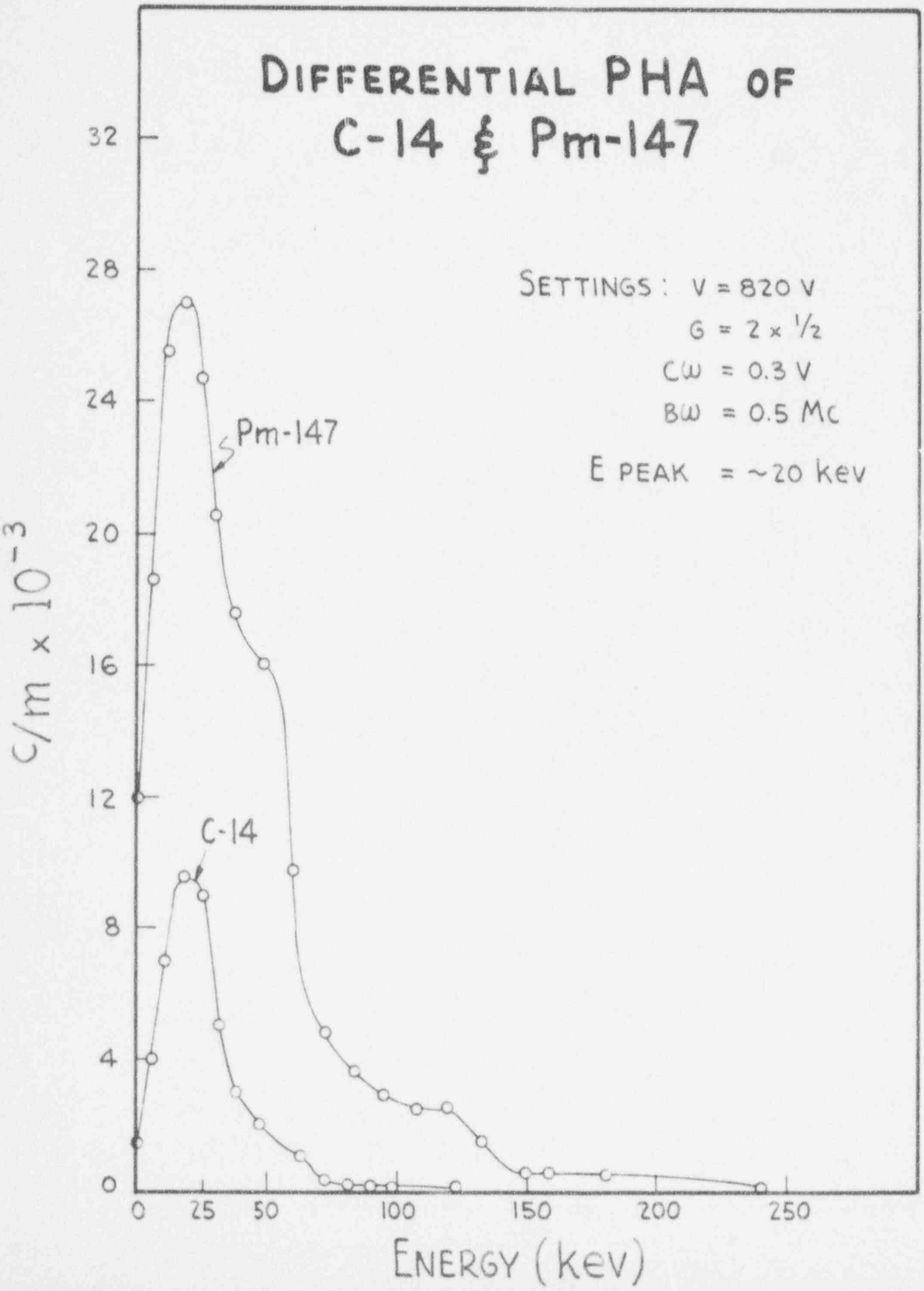
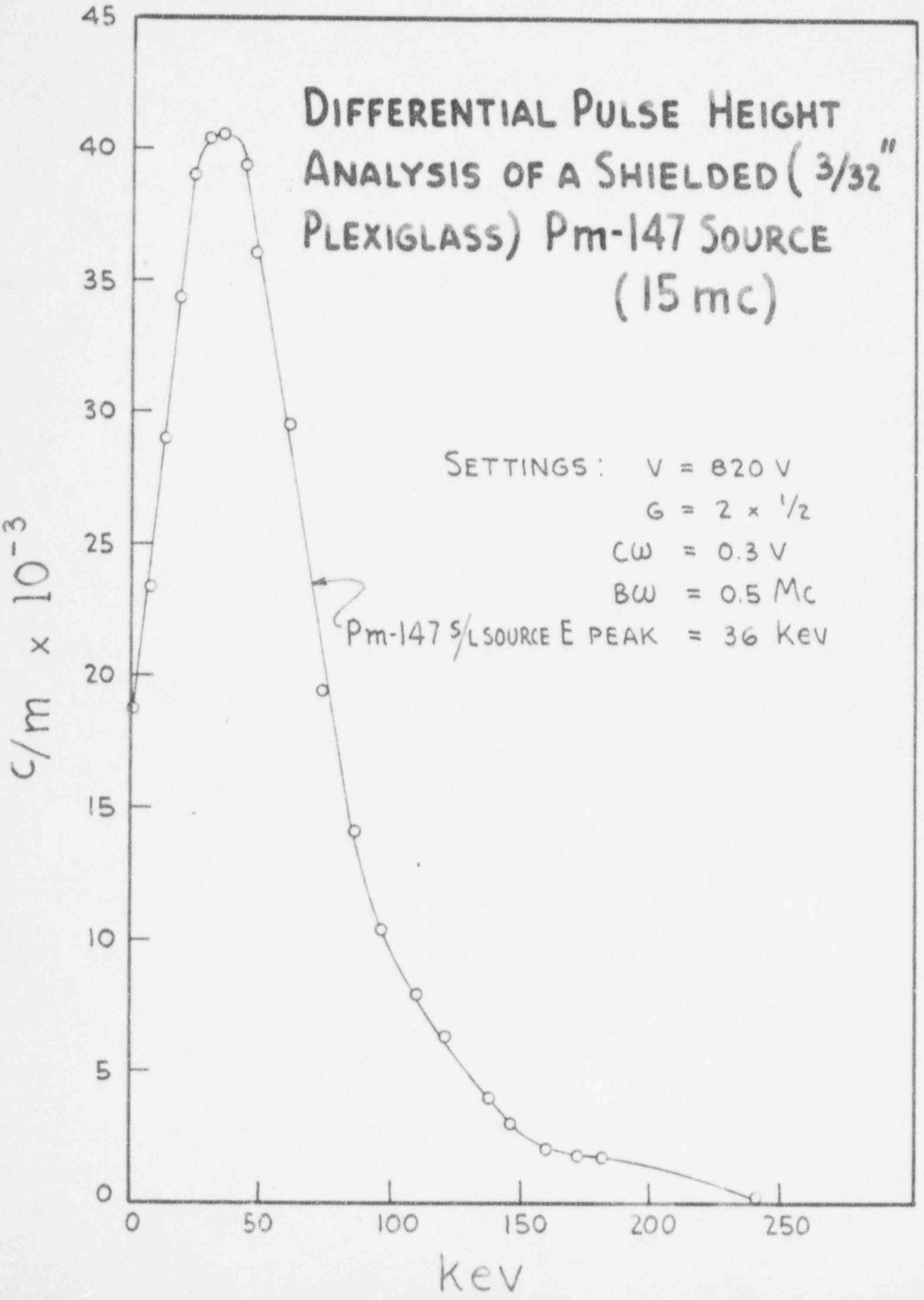

DIFFERENTIAL PHA OF
C-14 & Pm-147
SETTINGS : V = 820 V
G = 2 x 1/2
CW = 0.3 V
BW = 0.5 Mc
E PEAK = ~20 kev
Pm-147
C-14
C/m x 10^-3
0
4
8
12
16
20
24
28
32
0
25
50
100
150
200
250
ENERGY (kev)

FIG. 2


DIFFERENTIAL PULSE HEIGHT ANALYSIS OF A SHIELDED (3/32" PLEXIGLASS) Pm-147 SOURCE (15 mc)
SETTINGS: V = 820 V
G = 2 x 1/2
CW = 0.3 V
BW = 0.5 Mc
Pm-147 S/L SOURCE E PEAK = 36 Kev
C/m x 10^-3
45
40
35
30
25
20
15
10
5
0
0
50
100
150
200
250
kev

Appendix 3: Skin Dose from Pm-147 Betas

The important criterion in evaluating the hazard of a beta emitter such as Pm-147 is the dose delivered to the basal layer of the epidermis. The pertinent section in the Federal Register, Title 10, Part 20 (Appendix 1) sets the permissible weekly skin dose for the "hands and forearms or feet and ankles or head and neck" of any radiation as 1.5 rad at the basal layer of the epidermis. This, of course, applies to people in a restricted area. For the general public a value 1/10 of this number has been suggested. This defines the "permissible" dose. However, we are also interested in what dose is actually necessary to produce a discernible change in the skin since this helps put the problem in the proper perspective.

Experimental evidence[12] indicates that the skin is quite resistant to ionizing radiation. Moritz and Henniques[13] found a threshold surface dose of about 1500 rep from Sr-90 was required to produce a recognizable effect and that for soft beta emitters such as S-35 a dose of 20,000 rep was required. Using a Sr-90 source, Jacobsen[29] found that by giving rats a dose of 200 re, every 48 hours, the only observable response even after a total dose of 12,000 rep, was epilation. This treatment would be equivalent to a surface dose from a Pm-147 source of over 100,000 rep.

Figure 3 shows a plot of beta energy versus dose (delivered in a short time) required to produce recognizable damage to the skin.[14] The curve was plotted from data obtained with Y-91, Cs-137, Co-60 and S-35. The value for Pm-147 falls in the 10-15,000 rad range. Calculation of the energy absorbed in the epidermal layer of the skin (about 60 microns thick or 7 mg/cm^2) for the various beta emitters indicates that a dose of about 1500 rad must be delivered to the basal layer to produce a perceptible change. Therefore, only about 10% of the Pm-147 surface dose produces any effect on the skin. This means that a measured surface dose from our Pm-147 sources of 15 rad/week meets the Federal Register's "permissible" limit of 1.5 rad/week at the basal layer of the epidermis. (It would seem appropriate in measuring surface dose with Survey Instruments to use a window of 7 mg/cm^2. This has also been noted by Dunning[14] and Fitzgerald[15].)

The surface dose limits are now well defined. A dose of 15 rad/week (or 1.5 rad at the basal layer of the epidermis) is "permissible" and one of 10,000 rad is "emergency", and it

remains to measure or calculate the surface dose from a Pm-147 source. The most comprehensive review of the problem of surface dose from beta emitters has been made by Hine and Brownell.[5] They point out that the surface dose for beta applicators, which are equivalent to 3M self-luminous sources, cannot be calculated with any degree of reliability. Therefore, a number of one inch diameter self-luminous spots containing Pm-147 were prepared and the surface dose rates measured with survey type instruments (Table I). We recognize the inherent error in this method but the results should be within 50% of the true surface dose. Fitzgerald[15] found that the energy dependence correction factor for the Cutie Pie survey meter varied from 1.8 to 1.0 for beta emitters in the energy range 0.067 to 3.6 MEV. For Pm-147, the correction factor was 1.5. As an example of the range of values one obtains using different instruments, the surface dose of one of the sources was checked with various instruments and the results (Table II) indicate only a four-fold spread.

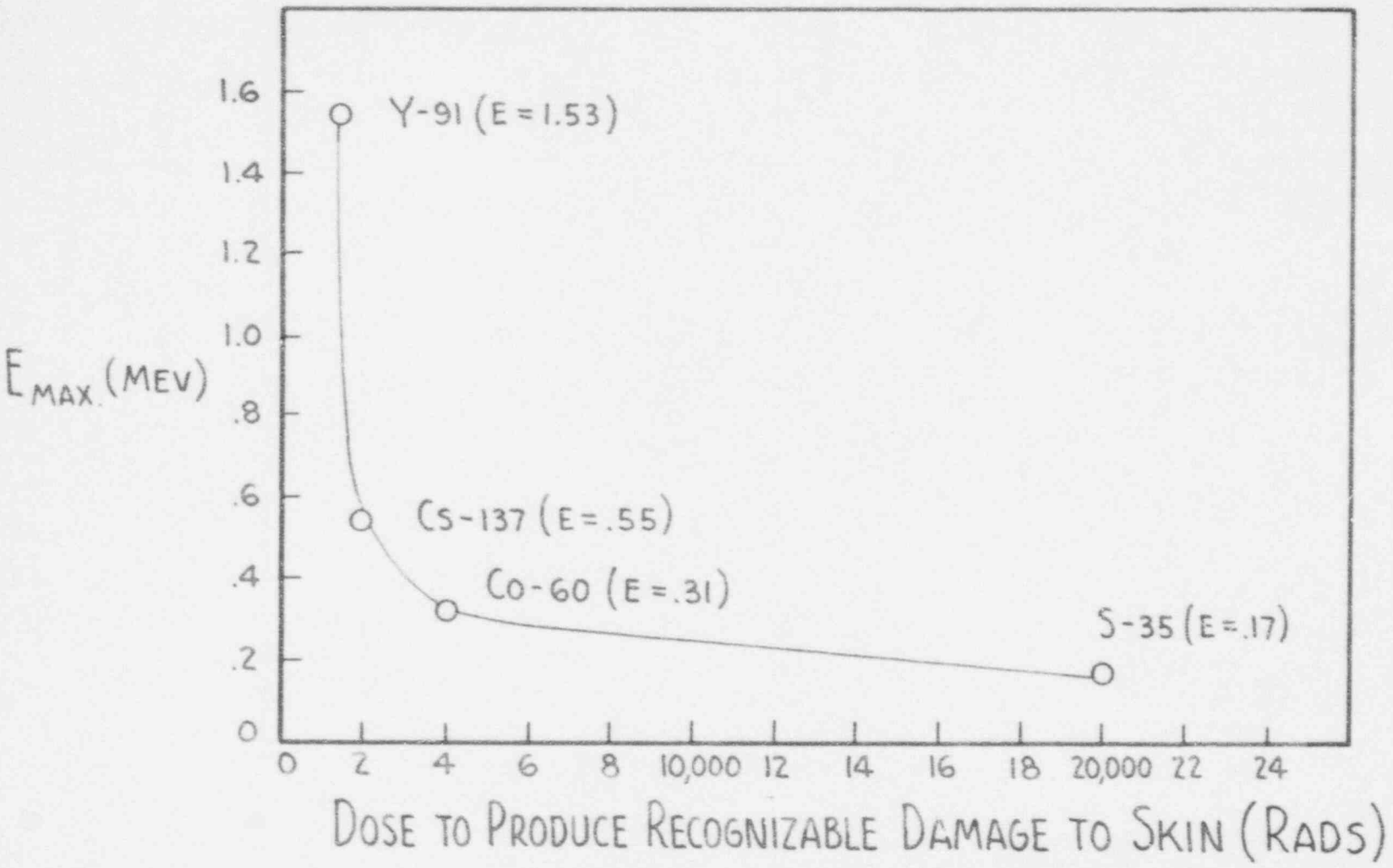


Fig. 3 Radiation Dose Needed to Produce Recognizable Damage to Skin as a Function of Beta Ray Energy.

Table I

Surface Dose Rate and Effect of Shielding on Pm-147

Self-Luminous Sources

Source (1" Diameter spots)	Radiation Dose Rate (mr/hr)[3]				
	No Shield	1/16" Plastic	1/8" Plastic	1/4" Plastic	Rubber Surgical Gloves, (25 mg/cm^2)
A 334 µc (No overcoat)	1050[1]	0.50	0.30	0.15	7.0[1]
B 355 µc[2] (One overcoat)	88[1]	0.35	0.20	0.13	1.3
C 346 µc (Two overcoats)	14.3[1]	0.22	0.15	0.10	0.45
D 367 µc (Three overcoats)	3.5	0.16	0.12	0.08	0.25

1. Dose rate measured with Nuclear-Chicago "Cutie Pie" Model 2586 (window thickness 7 mg/cm^2). All other measurements made with Geiger-Mueller PDR/27 Radiacmeter (window thickness 3.5 mg/cm^2).

2. This is one type of construction used in the 3M self-luminous devices. Note that the application of one "overcoat" of phosphor and binder reduces the surface radiation by more than 90%.

3. To convert these readings to those obtained with a "windowless" Cutie Pie Ionization Chamber, multiply by 4.4.

Table II

Comparison of Surface Dose Rates Measured

With Various Survey Type Instruments

Source (1" diameter spot)	Surface Dose Rate mr/hr			
	Cutie Pie Ionization Chamber		Nuclear-Chicago # 2612	PDR/27 Radiac-meter
	no window	7 mg/cm^2 window	1.4 mg/cm^2 window	3.5 mg/cm^2 window
367 µc (Three "overcoats")	15.1	3.5	9.0	3.5

Other data of interest are presented in Tables III-V. Table III shows the surface dose and brightness levels of some typical 3M Pm-147 activated watch dials. The average radium activated watch dial has a brightness in the 1-10 microlambert region.

Table III

Surface Dose Rate and Effect of Shielding

on 3M Pm-147 Self-Luminous Watch Dials

Brightness (micro-lamberts)	Amount of Isotope (microcuries)	Radiation Dose Rate (mr/hr)			
		No Shield	Rubber Surgical Gloves 16 mg/cm^2	1/16" Plastic	1/8" Plastic
150 µl	1000uc	750*	7*	0.50	0.30
20 µl	150	100*	2	0.35	0.20
6 µl	14	25*	1	0.22	0.15

*Dose Rate measured with Nuclear-Chicago "Cutie Pie" Model 2586 (window thickness 7 mg/cm^2). All other measurements made with Geiger-Mueller PDR/27 Radiacmeter (window thickness 3.5 mg/cm^2).

Table IV shows the effect of applying a thin plastic layer on a self-luminous watch dial. The coating can be sprayed or applied with a brush and can easily be made part of the dial painting procedure if considered desirable.

Table IV

Effect of Plastic Coating on Surface Dose Rate of a

Pm-147 Self-luminous Navy Submersible Wrist Watch

Coatings of Plastic *	Surface Radiation Level mr/hr
0	1200
1	600
2	350
3	220

*Dose measured with "Cutie Pie" survey meter (with 7 mg/cm^2 window)

The effect of distance on the dose rate for an unshielded 1 mc Pm-147 watch dial (Table V) shows how rapidly the rate falls off with distance.

Table V

Dose Rate and Distance Relationship of a 1 mc Pm-147 3M Self-Luminous Watch Dial (unshielded)

Distance From Watch Dial, Inches	Radiation Dose Rate* mr/hr
0	750
1/2	450
1	300
2	125
4	21
6	8
8	1.5
10	0 (background)

*Dose measured with "Cutie Pie" survey meter (with 7 mg/cm^2 window)

A specific example of the time limits for handling unshielded self-luminous sources made with 3M's Pm-147 microspheres can be given for the case of a watch dial. From the data in Table III, we see that a dial containing 1 mc of Pm-147 microspheres delivers a dose of 0.75 rads/hr to the basal layer of the epidermis. This means that a man could have the dials in direct contact with his skin for 2 hours a week and not exceed the "permissible" 1.5 r/week at the basal layer of the epidermis. With surgical rubber gloves, this dose rate is reduced by 99% to 7 mr/hr and the dials could then be handled continuously and not exceed the "permissible" limit.

It is of some interest to compare a "calculated" surface dose with the measured values (Tables I-IV). As an example of a "calculated" dose from a beta applicator, we refer to the book by Quimby et al[16], who use the charts and equations originally developed by Rossi and Ellis[17] to "calculate" the surface dose from various applicators. Using their procedure, we have calculated that a 1 mc/cm^2 Pm-147 source with no "overcoat" should give a surface dose of 75 rads/hour. For the 3M type self-luminous source which contains a 3 mil ($\sim$ 15 mg/cm^2) "overcoat" of phosphor and binder, the dose would be reduced by more than 90%[5]. Thus the calculated surface dose is 7.5 rad/hour. The measured dose is about 1.2 rad/hour.

Appendix 4: Leach data and animal feeding results for "3M" Brand Radiating Microspheres

1) Leach Data

Various isotopes were incorporated in 3M Microspheres and tested for integrity by soaking in various solvents for 7 days at 50° C. The amounts removed in % of original activity present are shown in Table VI.

Table VI

Test Reagent	Percent of Isotope Removed (7 days - 50° C.)			
	Pm-147	Sr-90	Cs-137	Po-210
0.01 N HCl	0.002	0.001	0.004	0.002
1% Versene	0.02	0.02	0.004	0.006

It is quite obvious from these data that the "3M" Brand Radiating Microspheres do an excellent job of immobilizing the radioactive isotopes. It is far superior to other systems used. For example, Table II shows a comparison between the ability of the 3M carrier and a commonly used material, montmorillonite, to retain radioactive Pm-147.

Table VII

Test Reagent	% of Pm-147 Isotope Removed (7 days-50° C.)	
	3M Microspheres	Montmorillonite
Water	0.007	2.0
5% NaCl	0.002	1.5
0.01N HCl	0.002	65.0

2) Animal Feeding Data

The animal feeding program was under the supervision of Dr. R. N. Bieter, University of Minnesota, and was performed in his laboratory. Four capsules were made up -- each containing about 0.5 - 0.6 mc of Sr-90 labelled microspheres (specific activity: 40 mc/gm). Each capsule was given to a male albino rat weighing 300-350 grams. The animals were kept in metabolism cages during the duration of the experiment. Two of the rats were sacrificed after one day and two after four days. The animals were autopsied and the gut and carcass dissolved separately by wet ashing in a sulfuric-nitric acid mixture. The data obtained are shown in Table VIII.

Table VIII

Location of Radioactivity in Rats Fed Sr-90 Labelled 3M Microspheres

Rat	Sacrificed at	% Urine	% Gut	% Carcass
1	1 day	0.016	23.4	0.0075
4	1 day	0.011	69.2	0.039
2	4 day	0.0056	0.035	$<$0.0007*
3	4 day	0.0043	0.078	$<$0.0007

*Lower limit of detection was 0.0007%.

It is apparent that the retention in the rat's body after four days is very low, less than 0.0007% of the dose given. As expected, practically none of the activity ($<$ 0.01%) was excreted in the urine with essentially all of it being in the feces. These data indicate a very high degree of retention of activity by the carrier and a large margin of safety in their use.

Not a great deal is known about the metabolism of Pm-147 in the human body. Durbin, et al[18] studied the absorption of the lanthanide elements, including Pm-147, in rats and found that absorption from intramuscular injection was, for the most

part, fairly complete. Deposition was primarily in the liver and skeleton. Elimination from the liver was fairly rapid with a half-time of 15 days. Elimination from the skeleton was slow with a half-time of approximately 2.5 years. Specifically, for Pm-147 one day after intramuscular injection, the following % of the initial dose was found: liver - 45%; skeleton - 35%. Absorption from gastrointestinal tract of the four isotopes studied (Ce-144, Eu-152, -154, Tb-160, and Tm-170) was less than 0.1% of the administered dose.

Appendix 5: Irradiation of Gastrointestinal Tract Upon Ingestion of Radioactive Isotopes

Calculation of Dose:

Calculation of the dose to the human gastrointestinal tract requires several simplifying assumptions. The result of this is the "averaging" of the dose through the whole gut. It should be understood that local areas may receive a much higher or lower dose than that predicted for the total tract.

The assumptions we shall make are as follows:

1. There is a uniform distribution of isotope throughout the gastrointestinal tract and all β-energy is absorbed in the tract. To simplify our calculations we have not taken into consideration the fact that the beta particles from weak emitters such as Pm-147 would largely be stopped in the aqueous medium in the gastrointestinal tract. The maximum penetration of Pm-147 betas in such a medium would be about 0.5 mm. The average penetration would only be about 20% of this, or 0.1 mm. Therefore, there is much doubt as to how much radiation would actually reach the walls of the tract.

2. The residence time of the isotope is 15 hours in the stomach[19,20] and small intestine together and 18 hours in the colon.

3. The mass of the stomach and small intestine is 1500 gm and the contents 500 gm; the mass of the colon is 500 gms and its contents 150 gms[20].

The formula we shall use to calculate doses is that of Thompson and Hollis[22];

$$D = \frac{2.3\ Q\ \bar{E}\ ct}{2\ w},$$

where D is the dose in reps; 2.3 is the dose rate in reps/hour from a concentration of one μc/gm of an isotope emitting a 1 MEV radiation in an extended medium; Q is the μc of isotope ingested; $\bar{E}$ is the average energy of the radiation in MEV; ct is the residence time of the radioisotope in the segment expressed in terms of portion of Q present (c) for an effective time, t (in hours); and w is the mass of the segment contents. The 2 in the denominator corrects the dose in the extended

medium to the dose at the segment wall[23].

The dose to the upper tract (stomach and small intestine) and lower tract caused by the ingestion of one millcure of Sr-90, Pm-147, and Cs-137, are calculated as follows:

1) Sr-90 $\bar{E} = 0.20 + 0.93 = 1.13$ MEV

Upper Tract $Q = 1000$ $c = 1$ $t = 15$ hours
$W = 500$

Then: $$D = \frac{2.3 \times 1000 \times 1.13 \times 1 \times 15}{2 \times 500} = 39 \text{ reps}$$

Lower Tract $Q = 1000$ $c = 1$ $t = 18$ $w = 150$

$$D = \frac{2.3 \times 1000 \times 1.13 \times 1 \times 18}{2 \times 150} = 138 \text{ reps}$$

2) Pm-147 $\bar{E} = 0.07$ MEV

Upper Tract $$D = \frac{2.3 \times 1000 \times 0.07 \times 1 \times 15}{2 \times 500} = 2.4 \text{ reps}$$

Lower Tract $$D = \frac{2.3 \times 1000 \times 0.07 \times 1 \times 18}{2 \times 150} = 9.7 \text{ reps}$$

Again, it must be emphasized that the true dose is only a fraction of this -- probably less than 10% -- due to energy adsorbtion in the aqueous contents of the tract.

3) Cs-137 $\bar{E} = 0.23$ MEV

Upper Tract $$D = \frac{2.3 \times 1000 \times 0.23 \times 1 \times 15}{2 \times 500} = 7.8 \text{ reps}$$

Lower Tract $$D = \frac{2.3 \times 1000 \times 0.23 \times 1 \times 18}{2 \times 750} = 32 \text{ reps}$$

Calculation of the γ-ray dose to the total body can be done in a very approximate manner. The total energy given off by the source is determined and it is assumed to be absorbed

totally and equally throughout the body. The total energy release ($E\gamma$) in ergs/sec-mc is calculated as follows:

$$E\gamma = 3.7 \times 10^{7} \frac{\text{dis}}{\text{sec-mc}} \times 0.66 \frac{\text{MEV}}{\text{dis}} \times 10^{6} \frac{\text{ev}}{\text{MEV}} \times 1.6 \times 10^{-12} \frac{\text{ergs}}{\text{ev}}$$

$$= 39 \frac{\text{ergs}}{\text{sec-mc}} \times 3600 = 140{,}000 \frac{\text{ergs}}{\text{hour-mc}}$$

Assuming total absorption in a 70,000 gm man, we have:

$$\frac{140{,}000}{70{,}000} \text{ gm} \quad \frac{\text{ergs}}{\text{hour-mc}} = \frac{2 \text{ ergs}}{\text{gm-mc-hr}}$$

Since 1 rep = 93 $\frac{\text{erg}}{\text{gram}}$; Dose = 0.02 r/hr from 1 mc Cs-137.

In the 30 hours in the body the total dose will be 0.02 x 30 or 0.6 r. This dose is a small percentage of the β dose to the gut.

Discussion of Results

When the approximate dose to the gastrointestinal tract has been calculated, one has the problem of deciding what does and does not constitute a harmful dose to the system. Rothe and Tuttle[24] report that a dose of 30 r/day for 10 days to the gastrointestinal tract of a rat causes only minimal histological changes. Quastler[25] has shown that mice are killed by an acute dose of 1200-10,000 r to the small bowel.

The severe gastrointestinal effects noted upon even small doses (50-100 r) of whole body radiation are well known, but are not generally considered to be due to radiation of the tract itself.

The question as to which organ is the most sensitive to radiation damage is not completely settled. Usually the colon is thought to be the sensitive organ, but Conrad [26] has suggested that the small intestine may be critical. He noted changes in the tone and motility of the rabbit intestine upon doses of 100 r. Spear[28], however, indicates that on the basis of radiological observations, the abdominal areas are unaffected by doses of hundreds of roentgens.

If one accepts a dose of 200 r to the colon as not likely to cause serious damage then one could consume 2 mc of Sr-90, 10 mc of Cs-137, or 30 mc of Pm-147 and expect no lasting ill effect. Probably the remarks of Conrad[26] are of some interest in this regard.

".....it should be stressed, that though the gastrointestinal tract is one of the most sensitive systems to ionizing radiation, it also has a most remarkable regenerative and reparative capacity. It takes doses well over a thousand roentgens to permanently damage the gut in most mammals studied, and it is capable of rapid, dramatic recovery of anatomical and functional integrity with doses in the lethal range".

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REPORT TO

MINNESOTA MINING AND MANUFACTURING COMPANY

On

ANIMAL STUDIES RELATED TO POSSIBLE RADIATION HAZARDS OF PROMETHIUM-147 CONTAINED IN 3M MICROSPHERES

Southern Research Institute
Birmingham, Alabama
September 18, 1961
6098-1255-I

ANIMAL STUDIES RELATED TO POSSIBLE RADIATION HAZARDS OF PROMETHIUM-147 CONTAINED IN 3M MICROSPHERES

ABSTRACT

To obtain information useful in assessing radiation hazards of Minnesota Mining and Manufacturing Company ceramic microspheres containing Pm^{147}, studies have been carried out on the retention and excretion of radioactivity by the rat after feeding of microspheres and on the damage to the skin of rabbit ears after prolonged exposure to devices containing microspheres.

Six rats were fed capsules containing approximately 25 mc (by 3M assay) of Pm^{147} and were sacrificed 24, 48, or 96 hours thereafter. Urine and feces were collected at 24-hour intervals up to the time of sacrifice, and these samples, the alimentary tracts, and the carcasses of the animals were assayed for radioactivity. The Pm^{147} was rapidly eliminated by all animals, and by 96 hours only very small amounts remained in the alimentary tracts. Small amounts of Pm^{147} were found in the carcasses of all, and in the urine of some, animals; but, excluding one animal that was an obvious anomaly, the combined amounts appearing in the urine and carcass did not exceed 12 parts per million of the administered dose.

Squares of aluminum covered with a paint containing radioactive microspheres were used to study the effects of radiation from Pm^{147} on the rabbit ear. Such devices, containing 20, 3, or 0.35 mc of Pm^{147}, were taped to the inside surface of the ear of a rabbit and allowed to remain for periods up to 90 days. Careful examination by a pathologist of the areas of skin exposed to these devices revealed no effects that were not also detected by examination of skin that had been exposed to devices containing non-radioactive microspheres.

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INTRODUCTION

This project was undertaken to obtain information on possible radiation hazards that might result from the ingestion by animals of Minnesota Mining and Manufacturing Company ceramic microspheres containing Pm^{147} or exposure of the skin of animals to devices containing these microspheres. The first study was designed to determine the amounts of Pm^{147} that could be detected in the carcasses or the urine of rats after feeding of radioactive microspheres. The second experiment was designed to study the effects on the skin of the rabbit ear of long exposure to devices containing radioactive microspheres. Each of these studies is described in detail below.

I. RETENTION AND EXCRETION OF PROMETHIUM-147 AFTER FEEDING OF PROMETHIUM-147-CONTAINING MICROSPHERES TO RATS

Materials and Experimental Animals

Microspheres containing Pm^{147} were furnished by 3M. These microspheres were described in a letter from Dr. J. W. Johnson of 3M, dated January 25, 1961, as having a specific activity of 890 μc per milligram. The rats used were males of the Wistar strain, and were purchased from Vinemont Animal Farms. The rats weighed 110-120 g at the time of administration of the microspheres.

Methods

Administration of Microspheres to Animals. - Microspheres were administered to the rats by capsule, which appeared to be the only practical method of administering a known weight of microspheres. In the absence of a commercially available capsule of appropriate size, capsules were made in our laboratories. For this purpose a copper wire was dipped into a 20% solution of gelatin and then twirled until the gelatin had set, after which the capsule was allowed to harden overnight in a stream of cool, dry air. The wire was then cooled in dry ice, and the capsule was removed. "Capsules" thus prepared were gelatin cylinders, of approximately 2 mm inside diameter and 10 mm in length, that were closed on one end. The open end was closed with a plug of agar just before administration to animals. A number of preliminary trials (a) established the technique for administering the capsules, (b) showed that the largest capsule that could be administered to a 100-g rat was one 3 mm in outside diameter, and (c) demonstrated that capsules filled with methylene blue were not broken during administration and were rapidly dissolved once they had reached the stomach.

For experiments with radioactive microspheres, a number of capsules were prepared and the best specimens, as determined by uniformity of diameter and smoothness of surface, were selected. Each tube was then tared and placed in a dust box, and a micro glass funnel was inserted well into the opening of the tube. Microspheres (approximately 25 mg, 22.2 mc by 3M analysis) were added to the top of the funnel which was tapped, if necessary, to transfer the radioactive material to the tube. Great care was taken in an attempt to avoid contamination of the outside of the tube, because any microspheres adhering to the somewhat sticky gelatin surface might be removed in the mouth of the animal and later contaminate the fur; therefore, any contamination of the outside of the capsule might result in presence of radioactivity in the carcass. After the tube had been thus filled, it was reweighed. The tube was closed by pressing the open end (handled by forceps) in a plate of agar just before administering the capsule to the animal. Vials filled in this manner were used both for assay of the microspheres and for administration to animals.

Rats were anesthetized with ether; when anesthesia was complete, capsules containing radioactive microspheres were placed at the back of the tongue (agar-plugged end first) and then forced down the throat with a greased glass rod of abou 3 mm in diameter. Each rat was then caged individually in a metabolism cage designed to permit separate recovery of urine and feces. There was considerable individual variation among the rats with regard to the rapidity of recovery from the anesthesia and the time at which they resumed consumption of food and water. Complete studies were done with six rats. In practice, one animal was first carried through the entire procedure as a final check on techniques, and then the remaining five animals were administered microspheres at the same time. Two animals were sacrificed at 48 hours after administration of the microspheres, two at 72 hours, and two at 96 hours. From all animals except the first 48-hour animal, urine and feces were collected at 24-hour intervals up to the time of sacrifice. All animals were assayed individually.

The animals were sacrificed with ether. A midline ventral incision was made and the skin was pinned back. The peritoneal and thoracic cavities were then opened and the alimentary tract (large and small intestine, stomach, esophagus, and the whole forward portion of the skull including the jaws) was removed with care to avoid rupture of the tract or contact of the mouth with the carcass. The latter precaution was taken to prevent contamination of the carcass with any microspheres that might have been in the oral cavity. No evidence of damage to the alimentary tract from feeding of the capsules was revealed at the time of dissection.

Urine was collected in the trap at the bottom of the metabolism cage, and the sides of the funnel leading to the trap were washed down

thoroughly to insure complete recovery. Since there was a possibility of contamination with microspheres from the feces, the urine was filtered twice before radioassay.

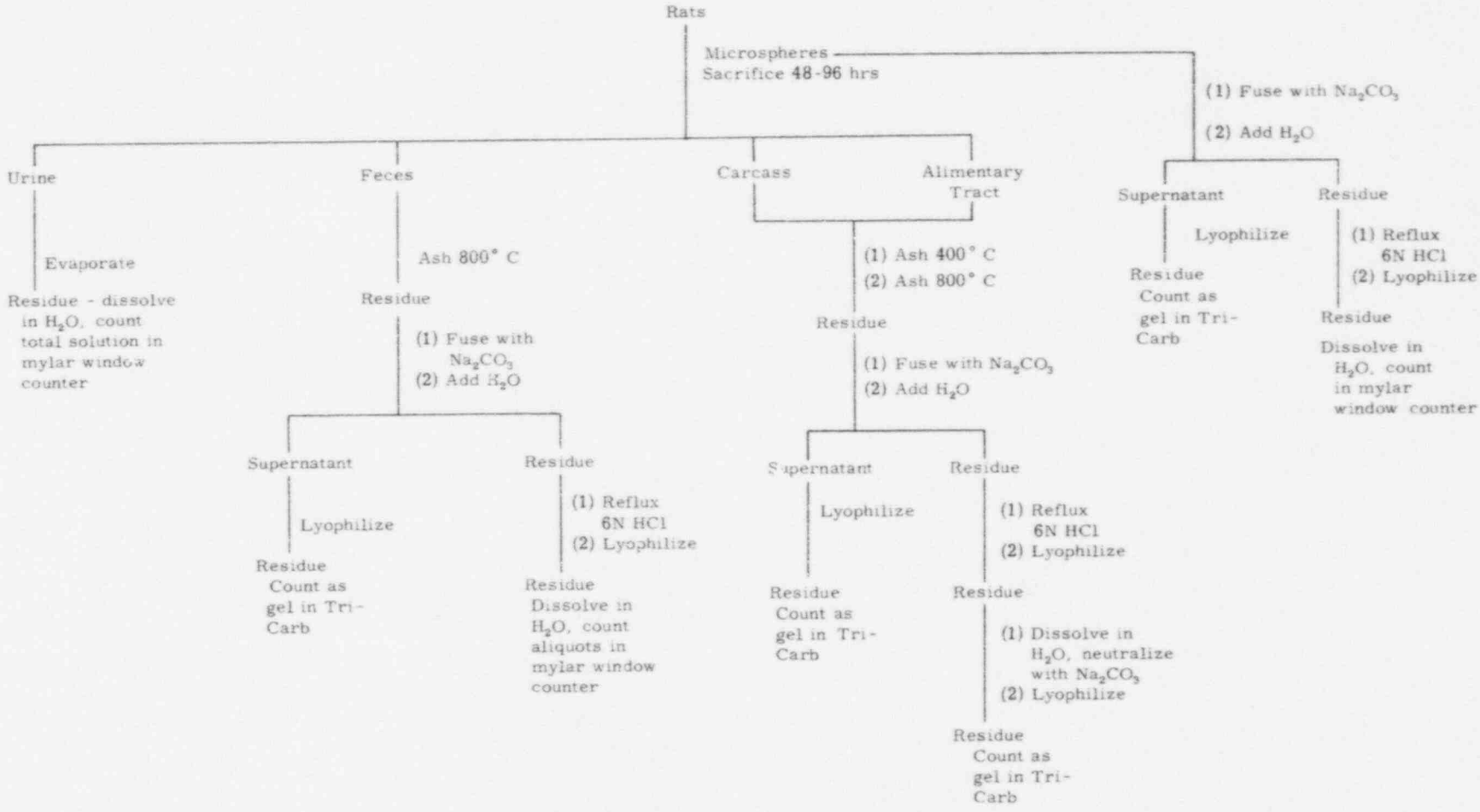
Sample Preparation and Radioassay. – It was considered essential that all samples be assayed in as nearly the same physical state as possible since the chief purpose of this effort was to determine the percentage of the administered Pm^{147} that was removed by contact with the alimentary tract of the animal. Two extremes in counting problems are presented by the microspheres on one hand and the carcass on the other, the microspheres containing a large amount of radioactivity in a small amount of material, and the carcass containing at the best trace amounts of radioactivity in a large amount of heterogenous material. It was considered essential to break up the beads in some manner that would release the Pm^{147} in a soluble form that could be sampled and assayed accurately. After several trials a procedure was developed using fusion with sodium carbonate as the first step. This fusion did not destroy the gross structure of the microspheres but when the water-soluble material was removed from the fusion mixture, the residual material, which contained virtually all of the Pm^{147}, was soluble in hot hydrochloric acid. This procedure was also used for feces, alimentary tract, and carcass. Although the carcass would not be expected to contain any intact microspheres, the same procedure was applied to it to insure a similar physical state of the sample to be counted. Outlines of the assay procedures are given in Chart 1 and details of each assay are given below. The results obtained are presented in Tables 1 and 2.

Microspheres. Capsules containing approximately 25 mg (22.2 mc by 3M assay) of microspheres were placed in a platinum crucible with 10 g of sodium carbonate, after which the crucible was heated in a muffle furnace at 900° C for 1 hour. The crucible and contents were allowed to cool, the crucible was filled with water, and the mixture was allowed to stand for 6 to 18 hours. After this treatment, the mixture was scraped from the crucible, transferred to a beaker, and heated to boiling. After being cooled, the mixture was centrifuged to yield a supernatant and a small insoluble residue. The residue was washed several times by centrifugation with a 5% solution of sodium carbonate. The supernatants from each sample were pooled separately.

The supernatants were lyophilized to dryness, after which samples of the residual solid (representing essentially all of the initial sodium carbonate) were weighed and weighed aliquots were suspended in a gel for radioassay. The gel, a mixture of Liquifluor (Pilot Chemical Company, Inc.) diluted

Chart 1

Outline of Methods of Assay of Microspheres and of Animal Samples



25-fold with reagent grade toluene and Cab-O-Sil (2.5% by weight), was homogenized for 5 minutes in a Waring Blendor. Fifteen milliliters of the gel was added to the sample in a glass counting vial, after which the mixture was shaken for 1 minute and finally assayed for radioactivity in a Packard Tri-Carb Liquid Scintillation Counter. If the amount of Pm^{147} in the lyophilized material was too great for accurate counting, a small amount, usually 50 or 100 mg., was placed in the counting vial with enough reagent grade sodium carbonate to bring the total to 1 g.

The water-insoluble residue remaining after the carbonate washes was refluxed with 20 ml of 6N hydrochloric acid for about 6 hours, at which time solution was complete. The entire fraction was then lyophilized to dryness in a system containing solid sodium hydroxide and the lyophilized residue was dissolved in distilled water. After appropriate dilutions, aliquot samples were placed on stainless steel planchets and evaporated to dryness on a warm hot plate. The samples were then counted in a Nuclear Measurements Proportional Counter PC3A with a two-inch mylar window counting chamber.

Feces. The feces samples were ashed at 800° C to remove the organic matter. The ash was then mixed with ten times its weight of sodium carbonate and the mixture was fused in a platinum crucible at 900° for 1 hour. The fusion mixture was then treated as described above for microspheres. When the lyophilized HCl solution from these samples was treated with water, the solution was not completely clear and radioassays on aliquots of these solutions showed considerable variation, no doubt as a result of non-uniformity of the sample. Since similar difficulties did not occur in the assays of the microspheres, it is presumed that some substance in the feces caused precipitation, co-precipitation, or occlusion of the promethium. This is the probable explanation of the fact that in five out of six animals, the assays showed somewhat more Pm^{147} in the feces than was actually administered. An exact determination of the feces content of Pm^{147} did not appear essential to the present study and, accordingly, no attempts were made to improve the assay of the feces.

Carcass. The whole rat, minus the alimentary tract, was ashed at 400° C for 6 hours or until a dry powdery ash

was obtained. The ash was then transferred to a platinum crucible and the temperature was brought to 800° C. After such treatment, the residual ash from a 100-g rat weighed approximately 3 g. An amount of sodium carbonate equal to four times the weight of the ash was added, and the mixture was fused at 900° C for 1 hour. The water-soluble fraction was separated in the same manner as described for the assay of the microspheres. The insoluble fraction was dissolved in hot hydrochloric acid and the resulting solution was lyophilized as has already been described for microspheres. When the residue from the lyophilization was dissolved in water, the solution was too acidic to be plated undiluted on steel planchets. Since the radioactivity of the carcass was low, it was desirable to count the entire sample; it was therefore neutralized with sodium carbonate and the resulting solution was lyophilized to dryness. The residue was then counted in a gel in the Tri-Carb Liquid Scintillation Counter, as has already been described.

Alimentary Tract. The alimentary tract, without removal of any contents, was ashed at 800° C and the ashed material was then assayed as described above for the carcass.

Urine. Urine samples were filtered twice to remove microspheres that might be present as a result of fecal contamination. The samples were evaporated to dryness and the residue was dissolved in 10 ml of water. The entire fraction was plated on stainless steel planchets, five or six planchets being used for each fraction; planchets were counted in the mylar window proportional counter. The solution plated contained some solid material and the radioactivity was not distributed uniformly among the planchets. The results presented in the tables represent the sum of the observed activity on all planchets made from a given sample.

Table 1

Radioactivity (cps/sample*) in Samples from Rats Administered Capsules of Microspheres Containing Pm^{147}

Animal No. and Time †	No. 1 (48 hr)	No. 2 (48 hr)	No. 3 (72 hr)	No. 4 (72 hr)	No. 5 (96 hr)	No. 6 (96 hr)
Wt. of Microspheres Administered	23.9 mg	31.8 mg	27.9 mg	27.9 mg	28.6 mg	23.1 mg
cps in Microspheres Administered*	0.88×10^8	1.18×10^8	1.03×10^8	1.03×10^8	1.06×10^8	0.86×10^8
Carcass	30.5	5.09	1,018	38,500	30.9	971
Urine 0-24 hrs		No Act.	No Act.	9.26	853	3.10
24-48 hrs	636	No Act.	No Act.	No Act.	No Act.	No Act.
48-72 hrs			No Act.	No Act.	No Act.	No Act.
72-96 hrs					No Act.	No Act.
Sum of Urine + Carcass	666.5	5.09	1,018	38,509	884	974
Alimentary Tract	148	5,834	5,669	55,056	5.78	4.80
Feces 0-24 hrs		1.90×10^8	1.49×10^8	1.69×10^8	1.38×10^8	1.06×10^8
24-48 hrs	0.75×10^8	2.50×10^6	7.04×10^6	9.58×10^6	0.05×10^6	2.94×10^6
48-72 hrs			7.23×10^4	5.50×10^4	0.14×10^4	4.18×10^4
72-96 hrs					0.30×10^3	4.5×10^3

* Calculated as observed cps in a mylar window counter uncorrected for counter efficiency.

† The indicated time is that elapsing between administration of the microspheres and the time at which the animals were sacrificed.

Table 2

Radioactivity (parts per million of the administered dose) in Samples from Rats Administered Capsules of Microspheres Containing Pm^{147}

		Animal No. 1 48 hrs*	Animal No. 2 48 hrs	Animal No. 3 72 hrs	Animal No. 4 72 hrs	Animal No. 5 96 hrs	Animal No. 6 96 hrs
Carcass		0.34	0.042	9.88	374	0.29	11.3
Urine	0-24 hrs		No Act.	No Act.	0.090	8.03	0.036
	24-48 hrs	7.2	No Act.	No Act.	No Act.	No Act.	No Act.
	48-72 hrs			No Act.	No Act.	No Act.	No Act.
	72-96 hrs					No Act.	No Act.
Sum of Urine + Carcass		7.54	0.042	9.88	374	8.32	11.3
Alimentary Tract		1.68	49.4	55.2	535	0.055	0.056

* The indicated time is that elapsing between administration of the microspheres and the time at which the animals were sacrificed.

Results and Discussion

The results obtained are presented in Tables 1 and 2. In Table 1, the values are given in observed counts; in Table 2, the results are given in parts per million of the administered dose. In the results of Table 1, a correction has been made for the difference in efficiencies of the Tri-Carb Liquid Scintillation Counter and the mylar window counter: the values given have all been corrected to counts observed in the mylar window counter. The reproducibility of the methods for sampling and assaying the microspheres was demonstrated in a number of assays with samples of small size and with capsules. Two radioassays of capsules containing about 15 and 25 mg of radioactive microspheres agreed within less than one per cent. It should be noted that these assays and those on smaller samples of microspheres showed a specific activity much less than that of the 3M assay reported in Dr. Johnson's letter. If it is assumed that in our counting systems the efficiency for Pm^{147} is slightly greater than that for C^{14}, our determination of specific activity of the microspheres is about 35% of the specific activity reported by 3M. Since all of the samples were counted in the same systems, the discrepancy between our assay and that of 3M is not critical for the interpretation of the results obtained.

From the results in Table 2, it is apparent that in three animals there was less than one part per million of the administered dose in the carcasses and in two others less than twelve parts per million. Animal no. 4 was apparently an anomaly with 374 parts per million in the carcass. This animal hemorrhaged slightly immediately after administration of the capsule, and this fact may possibly explain the relatively large amount of radioactivity found in the carcass. However, the damage to the alimentary tract that was manifested by the hemorrhaging was not detectable when the animal was sacrificed 72 hours later. It is also possible that this anomalous value may have resulted from contamination of the animal with feces, although the metabolism cage was designed to minimize this possibility. At any rate, since the amount of radioactivity in the carcass of this animal is of an entirely different order from that in the carcasses of any of the other five animals, it is probable that the results obtained with this animal can be ascribed to an artifact.

The amounts of radioactivity in the carcasses of the other five animals varied over a range of 0.042 to 11.3 parts per million. Some individual animal variation is to be expected. One may assume that the radioactivity present in the carcasses is Pm^{147} removed from the beads during their passage through the alimentary tract and that the amount so removed will vary directly with the length of time that the microspheres remain in the tract. This time will be subject to wide individual animal variations related to (a) the amount of foodstuff in the digestive system at

the time of administration of the microspheres; (b) the rapidity with which the animal recovers from the trauma of the administration of the capsule and from the anesthesia; (c) the rapidity with which the animal resumes consumption of food and water; and (d) the amount of food and water consumed during the experimental period.

Radioactivity was found in the urine of four of the six animals. Since the urine samples were filtered twice to remove any microspheres that might be present from contamination by feces, it is probable that the radioactivity in the urine represents Pm^{147} that had actually been removed from the microspheres and absorbed by the animal. In none of the animals, however, did radioactivity in the urine exceed ten parts per million of the administered dose and no radioactivity was found in the urine after 24 hours in animals no. 2-6 (only a 48-hr urine sample was obtained from animal no. 1). The sum of the radioactivities in the carcass and in the urine is a measure of the total amount of Pm^{147} absorbed from the microspheres during their passage through the animal, and from the results in Table 2 it will appear that, if animal no. 4 is excluded, this sum did not exceed twelve parts per million.

Since some microspheres might well be held up physically in the intestine, it is not unexpected that there should be wide variations in the amounts of radioactivity remaining in the alimentary tract. However, by 96 hours after feeding the tract was essentially free of radioactivity. It is also apparent from the results of Table 2 that more than 99% of all of the radioactivity that is excreted is excreted within the first 24 hours. The fact that some of the feces samples appear to contain more radioactivity than was administered has been discussed under "Methods."

Taken as a whole, the results would indicate that only very small amounts of Pm^{147} are absorbed by the animal from the microspheres. It is of some interest to extrapolate from rat to man and calculate the number of microcuries in the carcass for comparison with the permissible body burden of 60 μc established by the Atomic Energy Commisssion. In Table 3 are presented the man-equivalents of Pm^{147} calculated from the values obtained for the rat carcasses. For these calculations, 70 kg was taken as the weight of a man, and it was assumed that a man would absorb about the same percentage of Pm^{147} from ingested microspheres as would a rat. The calculated man-equivalents, then, would result from the ingestion by a 70-kg man of 70/0.12 times the amount of microspheres ingested by the rat, that is 0.025 x 70/0.12, or 14.5 curies of Pm^{147}. It is apparent from the results of Table 3 that in three instances the man-equivalents are well below the maximum permissible level and in two others are only two to three times this level (animal no. 4 is excluded for reasons already discussed). Thus, it might be estimated that, even after the ingestion of curie amounts of Pm^{147} in 3M microspheres by a man, the body burden of absorbed Pm^{147} would not

Table 3

Amounts of Pm^{147} in the Rat Carcass After Administration of Radioactive Microspheres and the Calculated Man-Equivalents

Rat No.*	Content of Pm^{147}		
	μc in Rat Carcass**	Man-Equivalent†	Fraction of Allowable Body Burden††
1	0.0092	5.37	0.090
2	0.0015	0.875	0.015
3	0.31	181	3.02
4	12	7000	117
5	0.0093	5.41	0.090
6	0.29	169	2.82

* Numbers correspond to those of Tables 1 and 2.

** The counting efficiency used to convert observed counts per second to microcuries is based on the 3M radioactivity of the microspheres. See text for further discussion.

† The number of μc in rat carcass multiplied by 70/0.12 (the weight of a man ÷ weight of rat, in kg).

†† The number of μc man-equivalents divided by the allowable maximum body burden of 60 μc (see, Federal Register, Title 10, Atomic Energy, Chapter 1 - Atomic Energy Commission, Part 20 - Standards for Protection Against Radiation, Appendix B, Table 3.)

exceed the allowable burden by more than three-fold, if at all. Moreover, since a typical 3M self-luminous device contains only about 25 mc of Pm^{147}, it is highly unlikely that an individual would ingest a curie amount of Pm^{147} in this form. It should be borne in mind that extrapolation from rodent to man are, at the best, crude approximations. Furthermore, these extrapolations are concerned only with the body burden of Pm^{147} resulting from absorption of this isotope from the ingested microspheres; no attempt was made to assess possible radiation damage to the intestine, an organ known to be highly sensitive to effects of radiation.

II. DETERMINATION OF SKIN SENSITIVITY TO AND POSSIBLE TISSUE DAMAGE DUE TO RADIATION FROM 3M SELF-LUMINOUS DEVICES

Experiments were conducted with rabbits to determine whether or not direct skin contact with devices containing various amounts of Pm^{147} in 3M microspheres and similar devices containing 3M microspheres but no Pm^{147} would result in tissue damage or irritation.

Materials and Methods

Experimental Animals. - Young adult female rabbits (New Zealand white strain) weighing between 2.5 and 3.0 kg each were obtained from a commercial breeder. Each animal was housed separately in a stainless steel cage of standard design throughout the course of the experiment. Each animal was given water and Purina Rabbit Checkers ad libitum.

Self-Luminous Devices. - 3M Company supplied Southern Research Institute with devices used in these experiments. These devices consisted of aluminum sheets of approximately 10 mill thickness and 1.3 cm square. Centrally placed on each sheet was an area 1 cm square covered with (a) 3M sulf-luminous paint containing no radioactivity or (b) 3M self-luminous paint containing Pm^{147}. The levels of Pm^{147} under (b) above were 350 μc, 3 mc or 20 mc in each device. The description of the radioactive devices supplied to Southern Research Institute was supplied in a letter from Dr. J. W. Johnson of 3M to Dr. L. L. Bennett, Jr., of Southern Research Institute dated January 25, 1961.

Method of Exposure and Evaluation of Skin Response to "Hot" and "Cold" Devices. - Nine rabbits were used. The central area of the inside surface of each ear was depilated by gentle plucking of the hairs and the bared area was cleansed with 95% ethanol to remove the natural surface oils to aid the adhesion of the binding tape.

The diagonally opposed corner outlines of a device were marked in each ear with india ink so that each device could be replaced in the identical area of previous exposure after each removal to examine for gross tissue response, replacement of the binding tapes, or other reasons. Figure 1 illustrates these exposure area identification marks.

A "cold" (non-radioactive) device was placed on the exposure area in the left ear of each rabbit, and a "hot" (radioactive) device was

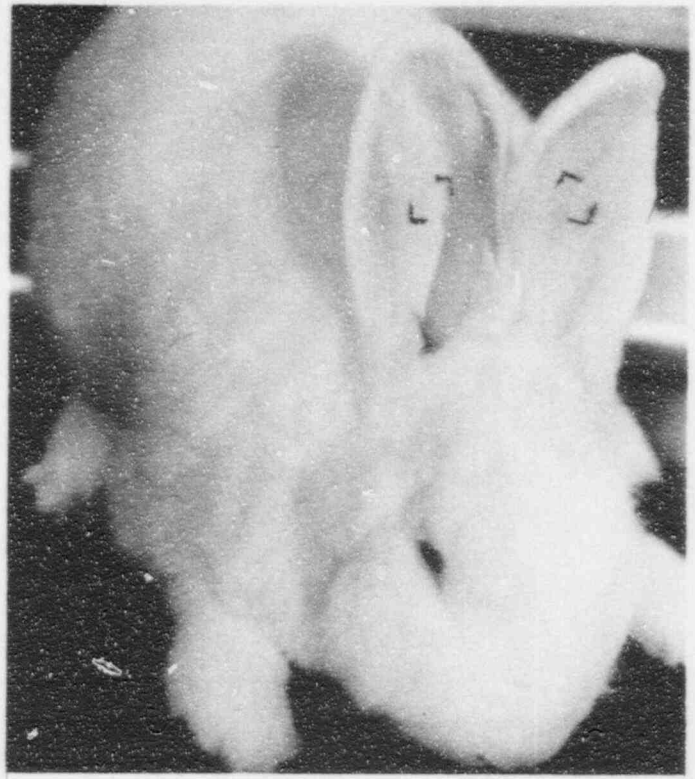


Figure 1. Exposure area identification marks in rabbit ears.

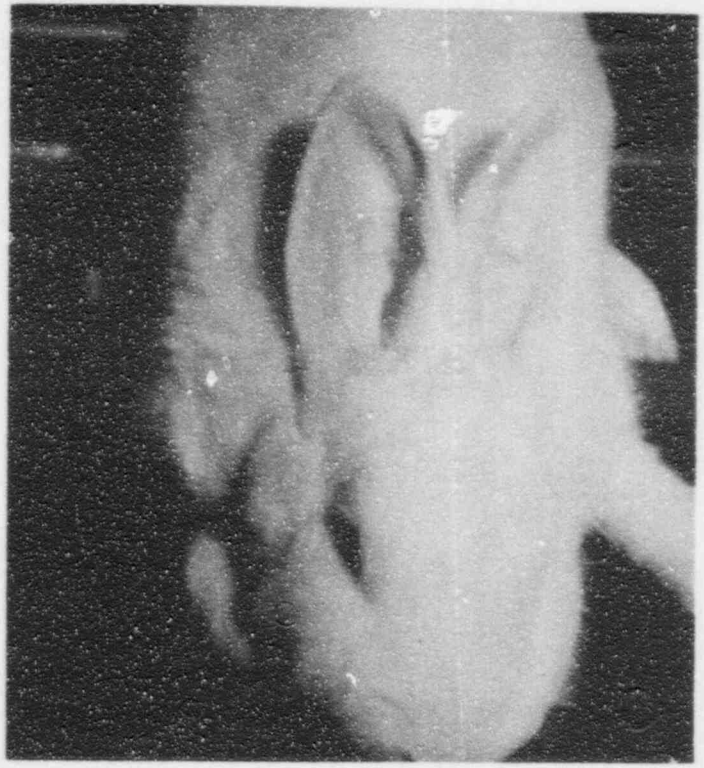


Figure 2. Devices taped in place in rabbit ears.

placed on the exposure area in the right ear of each rabbit; 3 rabbits were exposed to "hot" devices containing 350 μc Pm^{147}, 3 to "hot" devices containing 3 mc Pm^{147}, and 3 to "hot" devices containing 20 mc Pm^{147}. Each device was placed with the painted surface in direct contact with the skin. The devices were held in place with a piece of 3M microporous surgical tape (No. 530) as shown in Figure 2. Each ear was examined twice weekly during the exposure period for major gross signs of irradiation damage to the skin (erythema, edema, exfoliation, pigmentation, and necrosis) and other grossly apparent signs of abnormal tissue response to exposure to either the "hot" or "cold" devices.

After 30, 60, and 90 days total exposure one rabbit exposed to each level of Pm^{147} in the ear devices was sacrificed by air embolism and the area of skin in the ear exposed to the devices (both "hot" and "cold") were removed, fixed in 10% buffered formalin and submitted for histopathologic examination.

The histopathologic examinations were made by Dr. A. E. Casey. Dr. Casey is a pathologist of recognized competence. He is a charter member of the American College of Pathologic Anatomists and has extensive experience (over 30 years) in studying pathologic responses in experimental animals (especially mice, rats and rabbits) used in his own extensive and continuing laboratory research activities. At Dr. Casey's request all samples sent to him for histopathologic examination were submitted in code, to avoid the possibility of bias based on prior knowledge of the radiation exposure history of each sample. Copies of Dr. Casey's reports are appended to this report. We have also indicated on appendix page i the broken code and the date and identification number of each pathology report.

Following reporting of histopathological examination of all samples, we broke the code to Dr. Casey and asked him to re-examine all specimens to look for subtle tissue changes that might be evident with knowledge of radiation exposure history of each specimen. A copy of this report is on appendix page vii.

Results

At no time were any gross signs of radiation damage apparent during continuous exposure of rabbit skin to up to 20 mc of Pm^{147} and up to 90 days exposure. The exposed areas remained completely normal and without any gross evidence of erythema, edema, pigmentation, exfoliation or necrosis.

Table 4 summarizes the findings on histopathologic examination of tissue sections from the exposed areas. Dr. Casey was specifically requested to examine these specimens for typical signs of radiation damage to skin; e.g., atrophy of sebaceous glands, keratinization of the epidermis, widening of capillaries, increased mitosis in the dermal layers, etc.

Table 4

Summary of Histopathologic Findings in Rabbit Skin (ear) Exposed to "Hot" and "Cold" Devices for Periods up to 90 Days

Exposure	Duration	Histopathologic Findings
350 μc Pm^{147}	30 days	focal hyperkeratosis
"cold" device	30 days	superficial ulceration
3mc Pm^{147}	30 days	minimal hyperkeratosis
"cold" device	30 days	moderate hyperkeratosis
20 mc Pm^{147}	30 days	superficial ulceration
"cold" device	30 days	epidermal cyst, inflammation
350 μc Pm^{147}	60 days	subacute dermatitis and focal necrosis
"cold" device	60 days	chronic dermatitis
3 mc Pm^{147}	60 days	dermal scarring
"cold" device	60 days	subacute dermatitis
20 mc Pm^{147}	60 days	subacute dermatitis
"cold" device	60 days	subacute dermatitis
350 μc Pm^{147}	90 days	mild hyperkeratosis
"cold" device	90 days	hyperkeratosis
3 mc Pm^{147}	90 days	hyperkeratosis
"cold" device	90 days	hyperkeratosis
20 mc Pm^{147}	90 days	hyperkeratosis
"cold" device	90 days	no abnormalities

Examination of Table 4 reveals that some tissue reaction possibly associated with radiation damage might have occurred in the rabbit skin exposed to the "hot" devices. However, that the very slight histologic changes observed were due to response to radioactivity is most unlikely since:

1. Similar reactions, sometimes more extensive, were seen in the ear of the same rabbit exposed to the "cold" device as in the ear exposed to the "hot" device; e.g., 350 μc Pm^{147} and 3 mc Pm^{147} exposure for 90 days.

2. No consistent increase in pathologic response was observed in rabbit skin exposed to increasing levels of radiation from Pm^{147} as would be expected if the tissue reactions observed were due to the radiation itself and not to extraneous factors.

3. All of the tissue response observed could be expected to result from the irritation caused by prolonged exposure of an area of skin to a completely harmless foreign object such as the aluminum squares serving as the base for the actual radioactive device and the "cold" simulant devices used. Indeed, the failure to observe any skin reaction, either grossly or histologically, which might be attributable to the presence of Pm^{147} in the concentrations used in the "hot" devices when compared to the skin reaction to similar control "cold" devices leads us to the firm conclusion that such minor histologic changes as were seen were unrelated to the Pm^{147} contained in the devices used.

That, on the basis of observations in this report, up to 43,200 r or radiation (the total radiation at the surface produced by 20 mc of Pm^{147} in 90 days) was delivered to the rabbit skin examined without causing specific tissue reaction can only be interpreted, in our opinion, as evidence that this amount of soft β radiation is less than the amount necessary to cause specific damage to skin.

APPENDIX

Code to Duration and Intensity of Pm^{147} Exposure of Rabbit Ears Examined for Radiation Damage

Date	Pathology Report Number	Specimen Identification	Pm^{147} Exposure	Duration of Exposure
4/7/61	D-30624	A	350 μc	30 days
4/7/61	D-30624	B	cold	30 days
4/7/61	D-30624	C	3 mc	30 days
4/7/61	D-30624	D	cold	30 days
4/7/61	D-30624	E	20 mc	30 days
4/7/61	D-30624	F	cold	30 days
5/8/61	D-31332	S-1	350 μc	60 days
5/8/61	D-31332	S-2	cold	60 days
5/8/61	D-31332	S-3	3 mc	60 days
5/8/61	D-31332	S-4	cold	60 days
5/8/61	D-31332	S-5	20 mc	60 days
5/8/61	D-31332	S-6	cold	60 days
6/14/61	D-32654	A	3 mc	90 days
6/14/61	D-32654	B	cold	90 days
6/28/61	D-33026	A	350 μc	90 days
6/28/61	D-33026	B	cold	90 days
7/11/61	D-33341	A	20 mc	90 days
7/11/61	D-33341	B	cold	90 days

Received 4/8/61

Southern Research Institute 47-1961

F. M. Schabel, Jr. Project 1255 D-30624

These six bottles contain specimens of rabbit ear exposed for 30 days to β radiation from Pm^{147}. Three rabbits were used. One had a Pm^{147} device containing 350 μc taped to the inner surface of one ear and a similar non-radioactive device taped to the inner surface of the other ear. The second rabbit had a Pm^{147} device containing 3 mc taped to the inner surface of one ear and a cold device on the other. The third rabbit had a Pm^{147} device containing 20 mc taped to one ear and a cold device on the other ear. After 30 days total exposure the animals were sacrificed by an embolism, and the area of both ears which was directly under the "hot" and "cold" devices were removed, placed in 10% buffered formalin and submitted for pathologic examination.

We would like your careful examination of all samples for deviations from normal appearance of cells, tissues, vessels, nerves, etc. The samples are labeled 1 through 6, and we have the source code since Dr. Casey requested that we submit them to him blind.

Gross Description: M. Y. -pc

Received are specimens said to be rabbit skin numbered 1, 2, 3, 4, 5, and 6. No. 1 will be labeled A; No. 2 will be labeled B; No 3 will be labeled C; No 4 will be labeled D; No. 5 will be labeled E; and No. 6 will be labeled F.

Microscopic Examination and Diagnosis:

(A) Skin, ear - hyperkeratosis with pustule, focal
(B) Skin, ear - superficial ulceration with pyogenic reaction
(C) Skin, ear - hyperkeratosis, minimal
(D) Skin, ear - moderate hyperkeratosis with minimal neutrophilia
(E) Skin, ear - superficial ulceration and neutrophilia
(F) Skin, ear - epidermal inclusion cyst
(F) Skin, ear - vacuolar change, epidermis
(F) Skin, ear - inflammatory change, derma, mild

Comment: It is difficult to know whether the change in health was a part of the experimental program or not. The values for C and D are the least abnormal.

(signed) A. E. Casey, M. D.

Received 5/8/61

Southern Research Institute 5/8/61

Dr. F. M. Schabel, Jr. Project 1255 D-31332

These six bottles contain areas of rabbit ears exposed for 60 days to β-irradiation from Pm^{147}. These rabbits were used. One had a Pm^{147} device containing 350 μc taped to the inner surface of one ear and a similar non-radioactive device taped to the inner surface of the other ear as a control. The second rabbit had a Pm^{147} device containing 3 mc taped to the inner surface of one ear and a "cold" device taped to the inner surface of the other ear. The 3rd rabbit had a Pm^{147} device containing 20 mc taped to the inned surface of one ear and a "cold" device taped to the inner surface of the other ear.

After 60 days total exposure, the rabbits were sacrificed by air embolism, and the ones of both ears which were directly under the "hot" and "cold" devices were removed, placed in 10% formalin and submitted for pathologic examination.

We would like your careful examination of all samples for deviation from the normal appearance of cells, tissues, vessels, nerves, etc. The samples are labeled 1 thru 6, and we have the source code since Dr. Casey requested that we submit them to him in the blind.

Gross Description: T.R. -j

Received are 6 areas of rabbit ears labeled from samples 1 thru 6. Each section of rabbit ear skin consists of a square area, 1.8 cm on the side. Each one of these samples is labeled 1 thru 6. Each section of ear is bisected and embedded and given the same number as the bottle from which it came, 1 thru 6. Therefore, all samples are half embedded and half saved. 1xy for each sample.

Microscopic Examination and Diagnosis:

S1- Skin, ear - subacute dermatitis, moderate
S1- Skin, ear - scarring, derma
S1- Skin, ear - focal necrosis, collagen
S2- Skin, ear - perivascular reaction, moderate
S2- Skin, ear - scarring, derma
S2- Skin, ear - chronic dermatitis, focal
S3- Skin, ear - scarring, derma, reticular layer
S4- Skin, ear - subacute dermatitis, minimal
S5- Skin, ear - subacute dermatitis, moderate to marked
S5- Skin, ear - pustules and superficial ulceration
S6- Skin, ear - subacture dermatitis, minimal

(signed) A. E. Casey M.D.

Received 6/15/61

Dr. F. M. Schabel, Jr. 6/14/61

Southern Research Institute Project 1255 D-32654

These are sections of the ears from one rabbit exposed for 90 days to a radioactive device on one ear and an identical but "cold" device on the other ear. The bottle numbered 1 was exposed to a device containing 3 mc of Pm^{147}, and the bottle labeled 2 is the area of the other ear exposed to the cold device. The exposed area was the inner side of the ear (the one with the hair). We would like for you to compare these sections and give us your opinion as to whether or not the ear exposed to the "hot" device shows evidence of radiation damage, especially specific changes not seen in the opposite "cold" exposed control ear.

Gross Description: T.R. -f

Received is specimen No. 1 a portion of the skin from the ear of a rabbit. This piece of skin was exposed to a radioactive source. Half of the portion of this ear is cut into 2 sections for embedding and labeled A. 2xy

Specimen No. 2 consists of a similar portion of skin from the rabbit's ear. Both of these portions are layers of skin measuring about 1.5 cm in the side. This particular specimen No. 2 comes from an ear that was not exposed to the radioactivity. About half of this portion is also sectioned into 2 pieces for embedding and labeled B. 2xy

Gross Impression:

Portions of rabbit's ears:
1 exposed to radiation
1 not exposed to radiation

Microscopic Examination and Diagnosis:

(A) Skin, ear - hyperkeratosis with small pustule
(B) Skin, ear - hyperkeratosis

(signed) A. E. Casey, M. D.

Received 6/28/61

Southern Research Institute 6/28/61

Dr. F. M. Schabel, Jr. Project 1255 D-33026

These vials contain pieces of the ears of a rabbit exposed to a device containing 350 μc of Pm^{147} and an identical device which contained no radioactive material. The devices were taped to the inner surface of the ears for 90 days. The exposed surface was on the surface (inner) bearing the short hair. We would like to know if either of these sections show evidence of radiation damage and if so, which one and the degree and extent of damage. The radioactive material emits no gamma rays but only beta rays. The rabbit was numbered No. 1 and the two ear sections were labeled No. 1 and No. 2. The animal was sacrificed on June 26, 1961.

Gross Description: T.R. -f

Received are rabbit ear sections from a rabbit which were numbered No. 1. The section labeled No. 1 is labeled A for embedding purposes. The specimen consists of a rectangular piece of skin from the inner surface of the ear and measures 1.8 in length x 1.5 across. Sections are taken and labeled A from ear section No. 1.

Ear section No. 2 is a square piece of ear measuring 1.6 cm on the side. Sections are taken and labeled B. 2xy

Gross Impression:

Ear sections, rabbit No. 1 -

Microscopic Examination and Diagnosis:

Ear, (A) - inner surface - mild hyperkeratosis
Ear, (B) - hyperkeratosis with pustule

(signed) A. E. Casey, M. D.

Received 7/12/61

Southern Research Institute 7/11/61

Dr. F. M. Schabel, Jr. Project 1255 D-33341

These two bottles contain sections of the ear of rabbit No. 9 which was exposed to a radioactive device containing 20 mc of Pm^{147} for 90 days labelled No. 1, and the opposite ear which was exposed to an identical but non-radioactive device for 90 days labbelled No. 2.

The devices were taped to the inner surface of the respective ears, that is, the side of these sections with the short-fine hair.

We would like your opinion as to whether or not the ear exposed to the radioactivity shows any evidence of radiation damage, as compared to the control ear.

Gross Description: T. R. -j

Received as specimen No. 1 is a section from a rabbit ear measuring 1.5 cm on each side of a square section. This is labeled A. 2xy

Recieved as specimen No. 2 is a similar square of rabbit ear, labeled B. 2xy

Microscopic Examination and Diagnosis:

(A) Skin, ear - hyperkeratosis with pustule
(A) Skin, ear - chronic dermatitis, moderate
(B) Skin, ear - not remarkable

(signed) A. E. Casey, M. D.

Received 7/14/61

Southern Research Institute 7/11/61

Dr. F. M. Schabel, Jr. Project 1255 D-33026

Review of the ear slides knowing the identity of control and treated, as follows:

In the 3 controls D-30624 B, D and F, there was no ulceration of pustule formation or swelling of the nuclei or necrosis in D and F, minimal pustule in B. Slight reaction in subcutis in F. In each of the experimental D-32064 A, C, and E there was ulceration of the epidermis with neutrophilia and especially in C and E swelling of the epithelial cells of the epidermis compatible with the cytologic change in cancer or pre-cancer on Papanicolaou smears.

Review of D-33026. The B section shows some pustule possibly from pressure bandage. The experimental animal shows some swelling of the cells of epidermis in one area. Nuclei, enlarged cytoplasm, basophilic.

Review of D-31332. Slides 2, 4, and 6: No. 2 shows some perivascular collars of inflammatory cells and swelling of the collagen; No. 4 not remarkable; No. 6 shows a few lymphocytes and neutrophilis in the lower derma at one point. The experimental slides 1, 3, and 5: No. 1 shows an area of necrosis of epidermis and some perivascular collars and considerable cellular reaction in lower derma; No. 3 also shows superficial necrosis, perivascular collars in the derma; No. 5 shows extensive pustule formation with marked inflammatory reaction in derma on one surface of the ear, this is the most marked inflammatory reaction on the 6 slides.

Review of D-32654. The A portion shows small pustules in stratum corneum, very small. Almost no inflammation in derma. The B portion is essentially normal.

(signed) A. E. Casey, M. D.

ACKNOWLEDGMENTS

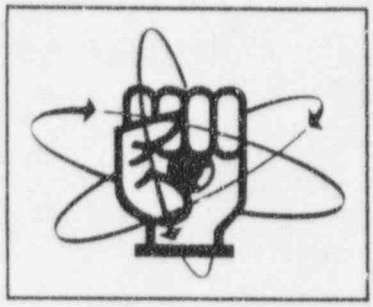
Miss Linda K. Simpson and Miss Jane Golden were responsible for the retention and excretion studies in rats and for radioassays. Dr. W. R. Laster supervised the studies with rabbits and also assisted in the administration of capsules to rats. Dr. William J. Barrett, Dr. Paul D. Sternglanz, and Mr. James P. Holmquist of the Analytical Chemistry Section devised the method for alkali fusion of microspheres.

Submitted by:

L. L. Bennett, Jr., Head
Biochemistry Division

F. M. Schabel, Jr., Head
Chemotherapy Division

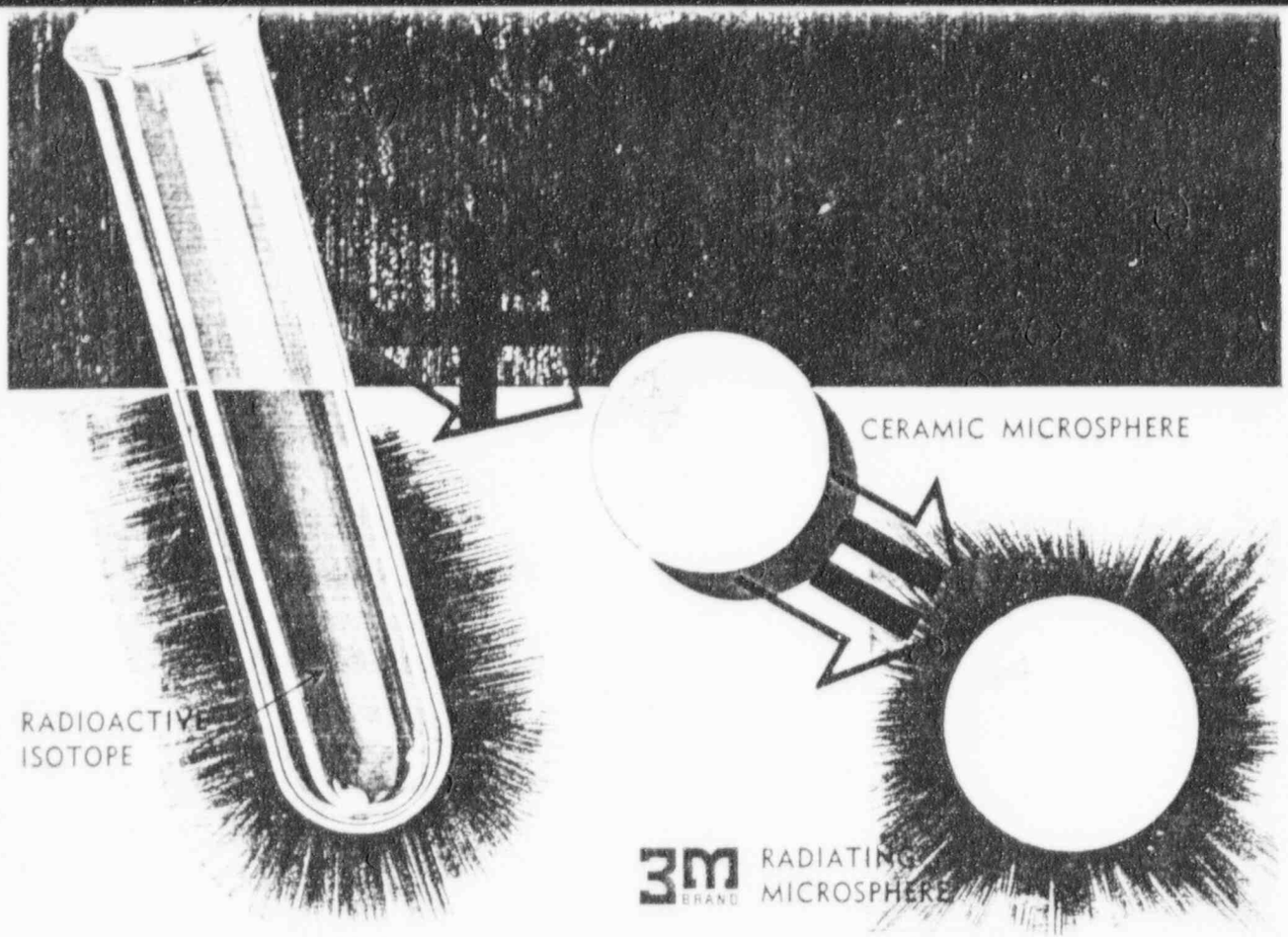
Birmingham, Alabama
September 18, 1961
6098-1255-I
NB 2448
nb (32)



3M Nuclear Products

3M MINNESOTA MINING & MANUFACTURING CO.

3M BRAND RADIATION SOURCES



■ 3M Brand Radiating Microspheres* represent a new approach to the utilization of radioactive materials. 3M scientists can introduce, and permanently "cage" a wide variety of radioisotopes in the solid ceramic carrier. The finished product is both physically and chemically inert, yet the useful radiation is allowed to escape with high efficiency.

■ Because of their unprecedented inertness and small size, 3M Brand Radiating Microspheres are finding wide acceptance where the danger of uncontrolled spreading of the free isotopes cannot be tolerated.

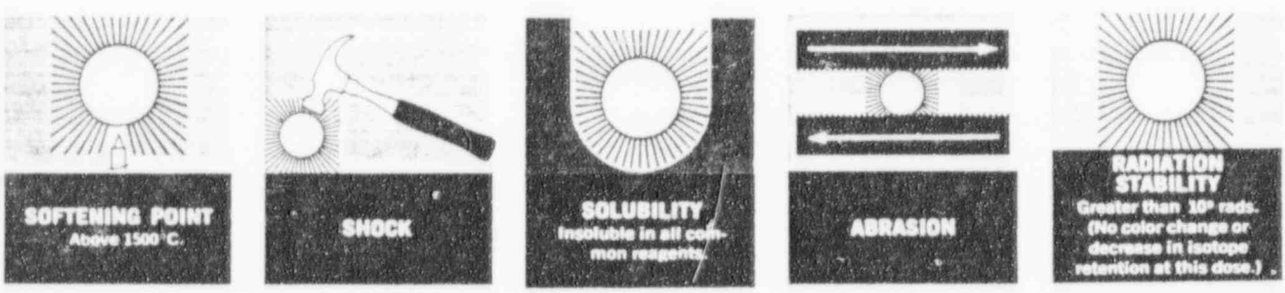
■ Industrial and tracer applications of 3M Brand Radiating Microspheres are even more varied and colorful, for the microspheres also have been found to be essentially insoluble in all common reagents —the softening point is above 1500°C—and they are not damaged by high radiation doses.

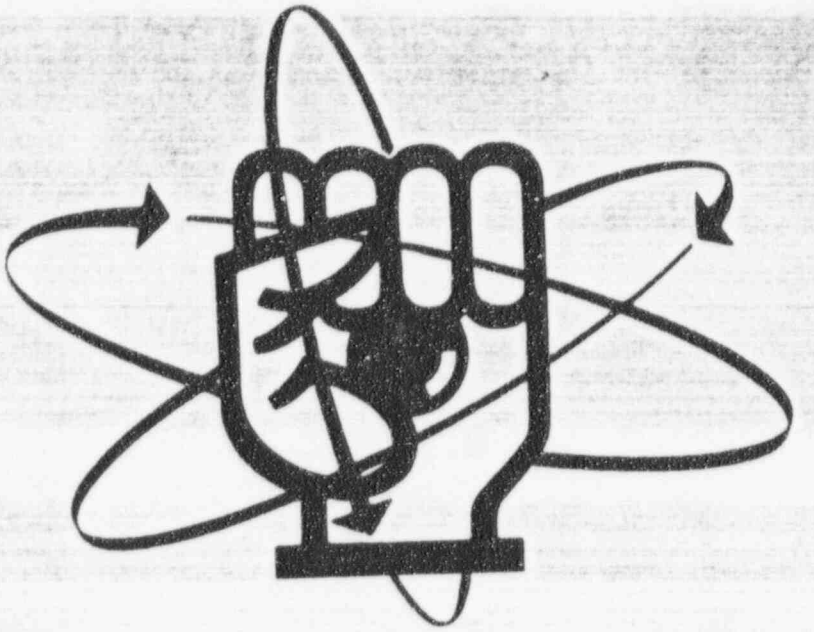
■ These tiny particles find use in any area where an inert, insoluble particulate tracer is required. These include sand tracers, fallout studies, and many others.

*Patent Pending

BASIC PROPERTIES

COLOR	DENSITY	SIZE
Milky white to clear	Absolute—3.0 g/cc. Bulk—About 2.0 g/cc.	Available in graded sizes from 15-150 microns





Licensing Information and Disclaimer

Shipments of radioactive isotopes are limited by law to those individuals who have in their possession a valid AEC or State License for the possession of such materials. A copy of this license or a signed statement giving the license number, isotope and possession limit must be in our hands before any shipment can be made.

All statements, technical information and recommendations contained herein are based on tests we believe to be reliable, but the accuracy or completeness thereof, is not guaranteed, and the following is made in lieu of all warranties, express or implied:

Seller's and manufacturer's only obligation shall be to replace such quantity of the product proved to be defective. Neither seller nor manufacturer shall be liable for any injury, loss or damage, direct or consequential, arising out of the use of or the inability to use the product. Before using, user shall determine the suitability of the product for his intended use, and user assumes all risk and liability whatsoever in connection therewith.

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Nuclear Products 3M COMPANY

ST. PAUL 1, MINN.

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- Self Luminous Materials
- Radioisotope Tracers
- High Surface Area Fuel Elements
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- Medical Microspheres
- High Temperature Reactor Fuels and Poisons

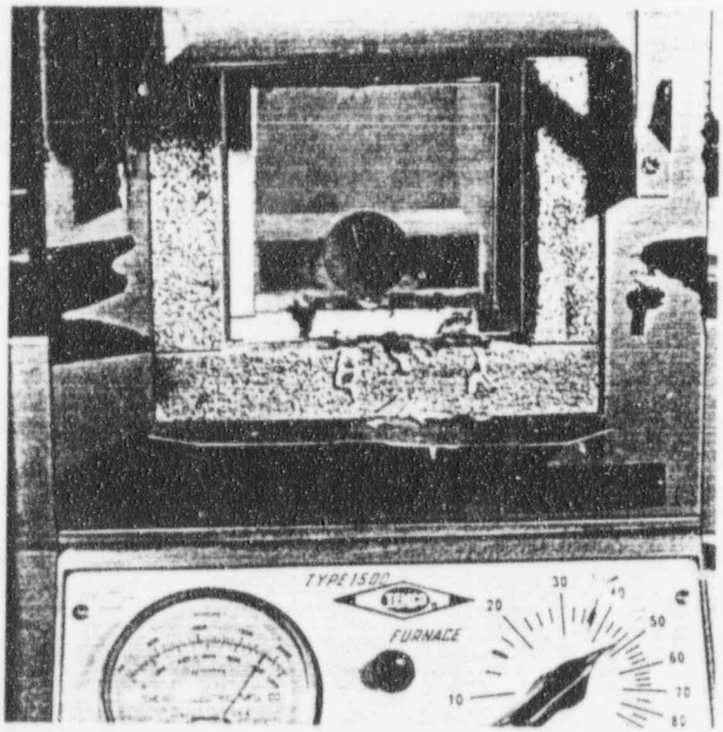
ISOTOPES AVAILABLE

Isotope	Half-Life	Emissions	Energies MEV	Bulk†	Line Source	Volume Source	Area Source	Ring Source	Point Source	Max. Sp. Act. mc/gm
Ag-111	7.6 d	Beta Gamma	1.04 < 10%	S	ns	ns	ns	ns	ns	1,000
Am-241	458 y	Alpha Gamma	5.48 .060	NA	S	S	S	S	S	50
Au-198	2.7 d	Beta Gamma	0.96 0.41	ns	ns	ns	ns	ns	ns	200,000
BaLa-140	12.8 d	Beta Gamma	1.02-0.48 0.03-0.54	S	ns	ns	ns	ns	ns	10,000
Cd-109	470 d	Gamma	.017	NA	ns	ns	ns	ns	ns	10,000
Cd-115	53 h	Beta Gamma	1.11-0.58 0.36-0.50, 0.53	ns	ns	ns	ns	ns	ns	10
Ce-141	33 d	Beta Gamma	0.58-0.44 0.15	S	ns	ns	ns	ns	ns	30,000
Ce-144	283 d	Beta Gamma	0.17, 0.3 0.134	NA	S	S	S	S	S	20,000
Co-58	72 d	Positron Gamma	.047 0.81	ns	ns	ns	ns	ns	ns	10,000
Co-60	5.2 y	Beta Gamma	0.306 1.17-1.33	NA	S	S	S	S	S	1,000
Cr-51	27.8 d	Gamma	0.32	ns	ns	ns	ns	ns	ns	1,000
Cs-137	30 y	Beta Gamma	0.52 .662	NA	S	S	S	S	S	10,000
Fe-59	45 d	Beta Gamma	0.46-0.27 1.10-1.29	ns	ns	ns	ns	ns	ns	100
Hg-203	45 d	Beta Gamma	0.208 0.279	S	ns	ns	ns	ns	ns	500
Kr-85*	10.5 y	Beta Gamma	0.67 0.15	NA	S	S	S	S	S	
La-140	40 h	Beta Gamma	1.34-2.15 0.09-1.60	ns	ns	ns	ns	ns	ns	10,000
Na-22	2.6 y	Positron Gamma	.54 1.23	NA	ns	ns	ns	ns	ns	100
P-32	14.3 d	Beta	1.701	ns	ns	ns	ns	ns	ns	10,000
Pm-147	2.6 y	Beta	0.223	NA	ns	ns	S	S	S	50,000
Po-210	138 d	Alpha	5.3	NA	ns	ns	S	S	S	10,000
Pr-143	13.7 d	Beta	0.93	ns	ns	ns	ns	ns	ns	10,000
Rb-86	18.6 d	Beta Gamma	1.77 1.08	S	ns	ns	ns	ns	ns	500
S-35	87.1 d	Beta	0.167	ns	ns	ns	ns	ns	ns	10,000
Sc-46	85 d	Beta Gamma	0.36 0.89-1.12	S	ns	ns	ns	ns	ns	6,000
Sr-85	65 d	Gamma	0.013-0.513	ns	ns	ns	ns	ns	ns	9,000
Sr-89	50 d	Beta Gamma	1.463 0.91	ns	ns	ns	ns	ns	ns	9,000
Sr-90	28 y	Beta	0.61	NA	S	ns	S	S	S	10,000
Tl-204	4 y	Beta	0.77	NA	ns	ns	ns	ns	ns	1,000
Tm-170	129 d	Beta	0.88	NA	ns	ns	ns	ns	ns	1,000
U-238	4.5 x 10^9	Alpha Gamma	4.18 0.05	NA	S	S	S	S	S	.0001
Y-90	64 h	Beta	2.18	S	ns	ns	ns	ns	ns	25,000
Y-91	61 d	Beta Gamma	0.33-1.53 1.19	ns	ns	ns	ns	ns	ns	10,000
Yb-169	32 d	Gamma	0.06-0.20	S	ns	ns	ns	ns	ns	15,000
Zn-65	250 d	Beta Gamma	.3 1.12	NA	ns	ns	ns	ns	ns	250

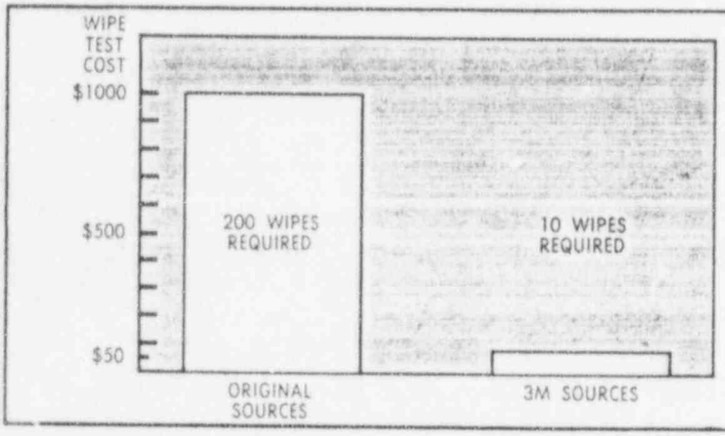
*—Gas
†S—Standard
ns—Non-standard, special order
NA—Not Available in Bulk

3M BRAND RADIATION SOURCES

■ Having successfully developed the Radiating Microspheres, 3M's Nuclear Products Laboratory began developing a complete line of radiation sources. These sources, using 3M Brand Radiating Microspheres, are unlike ordinary sources; they offer you DOUBLE SAFETY. With the isotope securely caged in the microspheres and the microspheres safely sealed in corrosion resistant capsules, 3M makes the highest integrity sources available.



■ 3M Brand Radiation Source Model 3A1F heated at 1000 °C for thirty minutes, then quenched in water to simulate condition of plant fire. After this severe thermal shock, tests showed no leak or loss of activity.

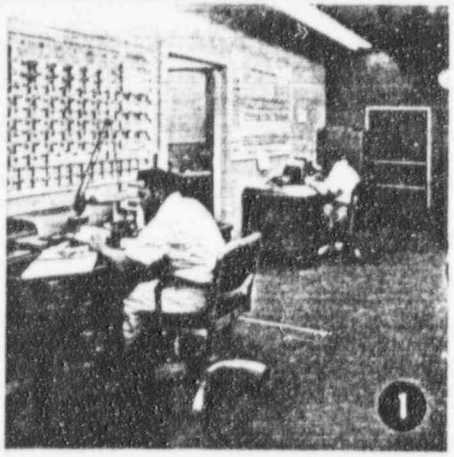


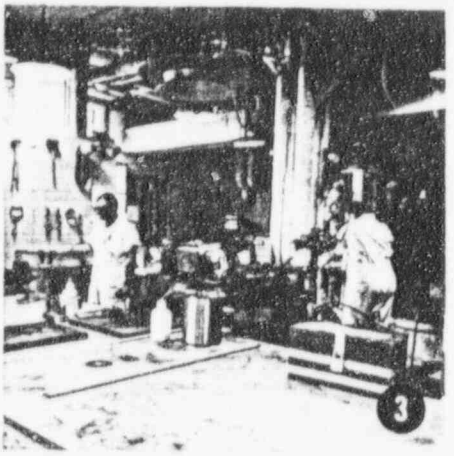
■ Chart shows savings a 3M customer gained by changing to 3M Brand Radiation Sources.
Wipe test relief given by A.E.C. to 3M source. 10 wipe tests per 100 sources per year.

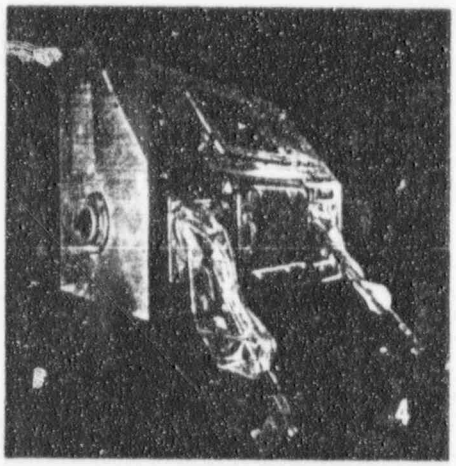
Original sources required 200 wipe tests per 100 sources per year.
Net savings per year of $950.00. ■

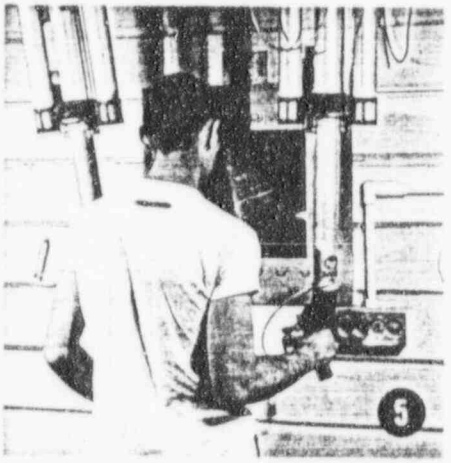
You may wish to utilize the sources we are producing, or you may wish us to design a source to your own requirements; in either case this brochure will provide a working familiarity with our products and concepts.

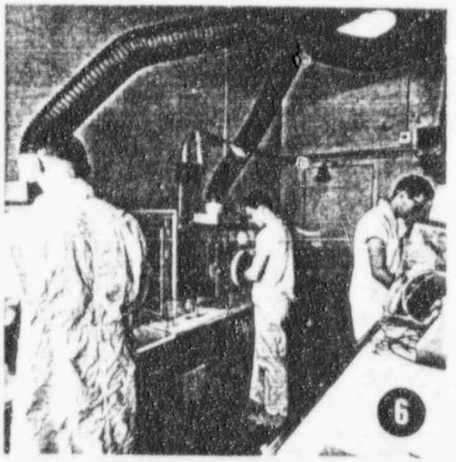
3M Nuclear Products
MINNESOTA MINING & MANUFACTURING CO.

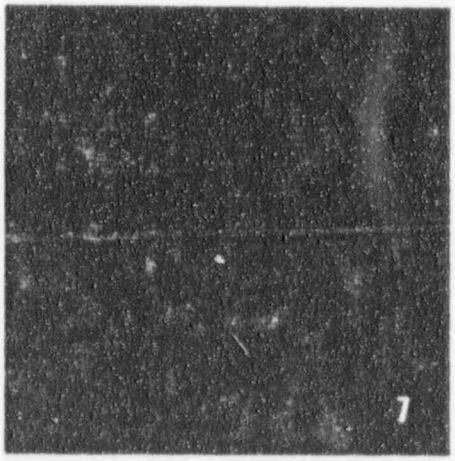


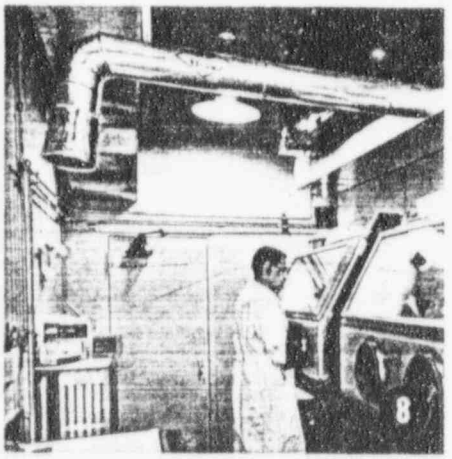


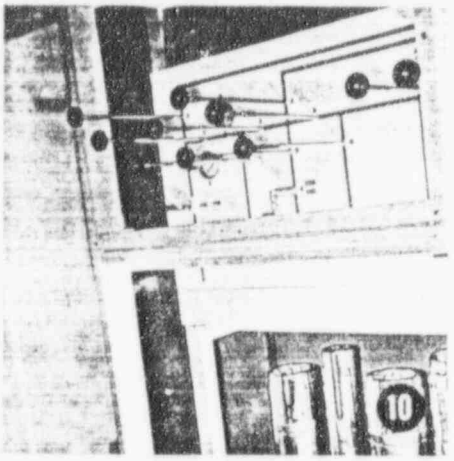


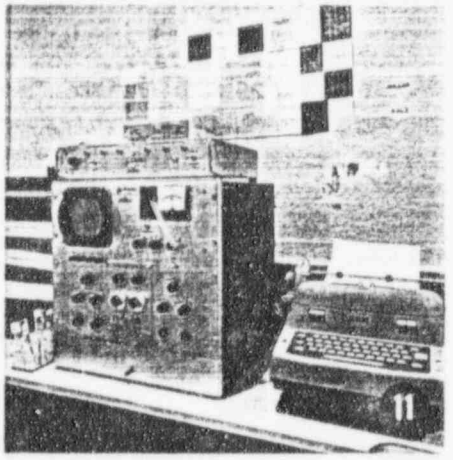












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Nuclear Products 3M COMPANY

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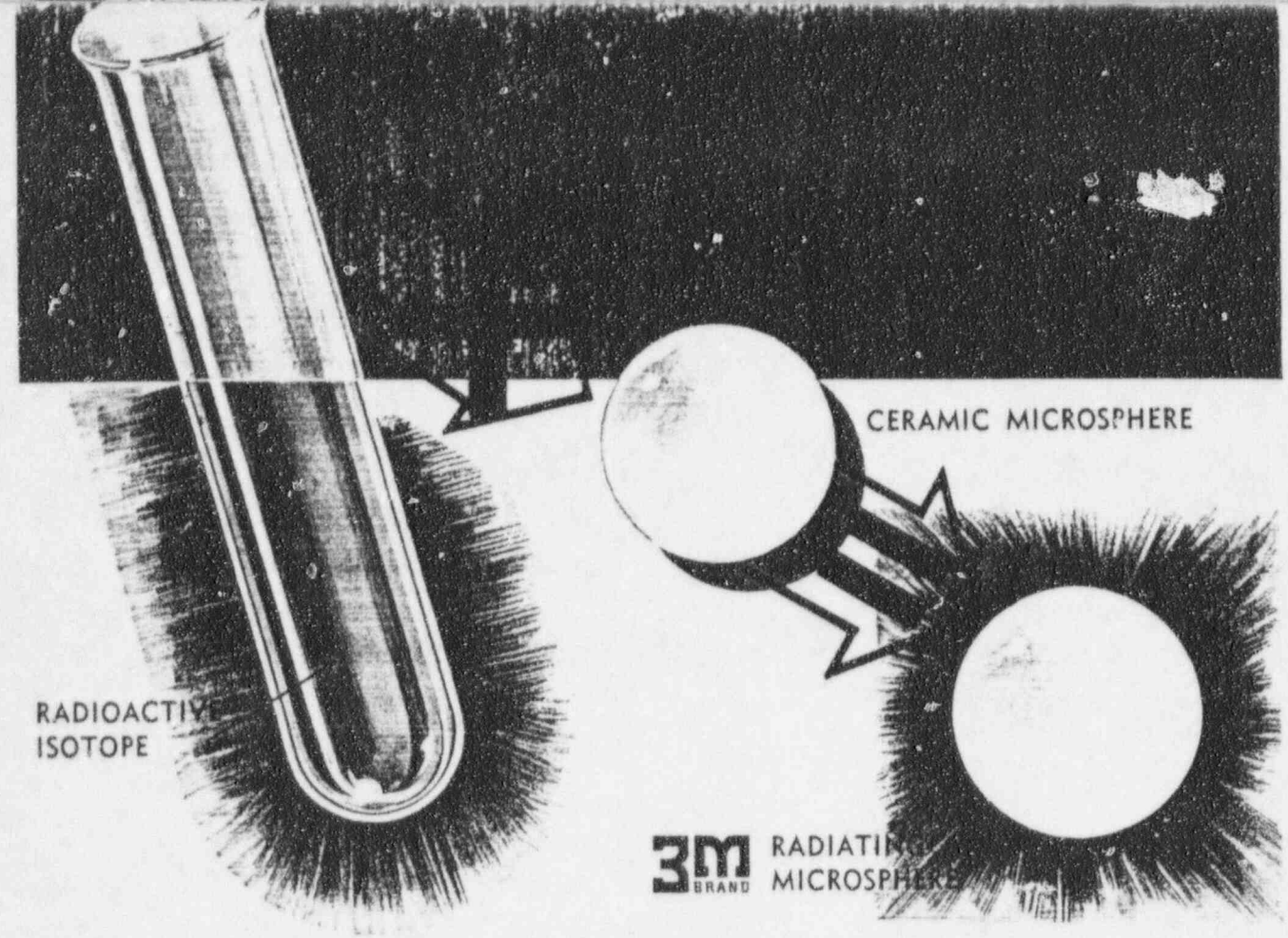


■ 3M Brand Radiating Microspheres* represent a new approach to the utilization of radioactive materials. 3M scientists can introduce, and permanently "cage" a wide variety of radioisotopes in the solid ceramic carrier. The finished product is both physically and chemically inert, yet the useful radiation is allowed to escape with high efficiency.

■ Because of their unprecedented inertness and small size, 3M Brand Radiating Microspheres are finding wide acceptance where the danger of uncontrolled spreading of the free isotopes cannot be tolerated.

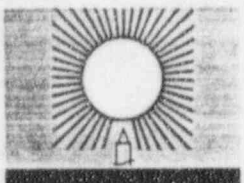
■ Industrial and tracer applications of 3M Brand Radiating Microspheres are even more varied and colorful, for the microspheres also have been found to be essentially insoluble in all common reagents —the softening point is above 1500°C—and they are not damaged by high radiation doses.

■ These tiny particles find use in any area where an inert, insoluble particulate tracer is required. These include sand tracers, fallout studies, and many others.

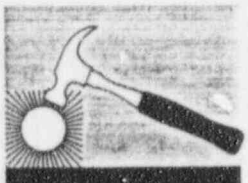
Patent Pending

BASIC PROPERTIES

COLOR	DENSITY	SIZE
Milky white to clear.	Absolute—3.0 g/cc. Bulk—About 2.0 g/cc.	Available in graded sizes from 15-150 microns.

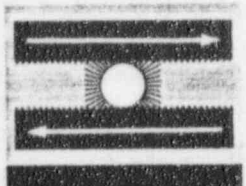


SOFTENING POINT
Above 1500°C



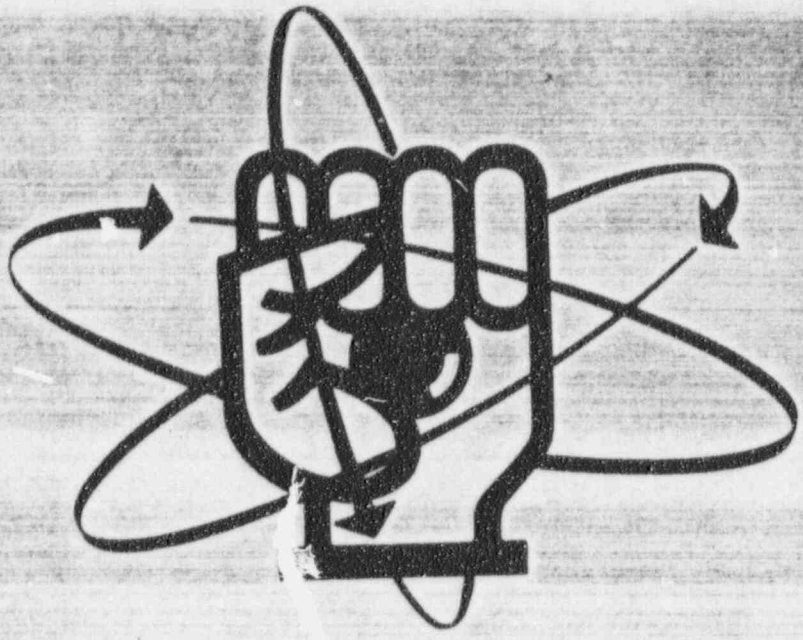
SHOCK

SOLUBILITY
Insoluble in all common reagents



ABRASION

RADIATION STABILITY
Greater than 10^8 rads. (No color change or decrease in isotope retention at this dose.)



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BaLa-140	12.8 d	Beta Gamma	1.02-0.48 0.03-0.54	S	ns	ns	ns	ns	ns	10,000
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Cd-115	53 h	Beta Gamma	1.11-0.58 0.36-0.50, 0.53	ns	ns	ns	ns	ns	ns	10
Ce-141	33 d	Beta Gamma	0.58-0.44 0.15	S	ns	ns	ns	ns	ns	30,000
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Co-58	72 d	Positron Gamma	.047 0.81	ns	ns	ns	ns	ns	ns	10,000
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Cr-51	27.8 d	Gamma	0.32	ns	ns	ns	ns	ns	ns	1,000
Cs-137	30 y	Beta Gamma	0.52 .662	NA	S	S	S	S	S	10,000
Fe-59	45 d	Beta Gamma	0.46-0.27 1.10-1.29	ns	ns	ns	ns	ns	ns	100
Hg-203	45 d	Beta Gamma	0.208 0.279	S	ns	ns	ns	ns	ns	500
Kr-85*	10.5 y	Beta Gamma	0.67 0.15	NA	S	S	S	S	S	
La-140	40 h	Beta Gamma	1.34-2.15 0.09-1.60	ns	ns	ns	ns	ns	ns	10,000
Na-22	2.6 y	Positron Gamma	.54 1.23	NA	ns	ns	ns	ns	ns	100
P-32	14.3 d	Beta	1.701	ns	ns	ns	ns	ns	ns	10,000
Pm-147	2.6 y	Beta	0.223	NA	ns	ns	S	S	S	50,000
Po-210	138 d	Alpha	5.3	NA	ns	ns	S	S	S	10,000
Pr-143	13.7 d	Beta	0.93	ns	ns	ns	ns	ns	ns	10,000
Rb-86	18.6 d	Beta Gamma	1.77 1.08	S	ns	ns	ns	ns	ns	500
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Sr-90	28 y	Beta	0.61	NA	S	ns	S	S	S	10,000
Tl-204	4 y	Beta	0.77	NA	ns	ns	ns	ns	ns	1,000
Tm-170	129 d	Beta	0.88	NA	ns	ns	ns	ns	ns	1,000
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Y-91	61 d	Beta Gamma	0.33-1.53 1.19	ns	ns	ns	ns	ns	ns	10,000
Yb-169	32 d	Gamma	0.06-0.20	S	ns	ns	ns	ns	ns	15,000
Zn-65	250 d	Beta Gamma	.3 1.12	NA	ns	ns	ns	ns	ns	250

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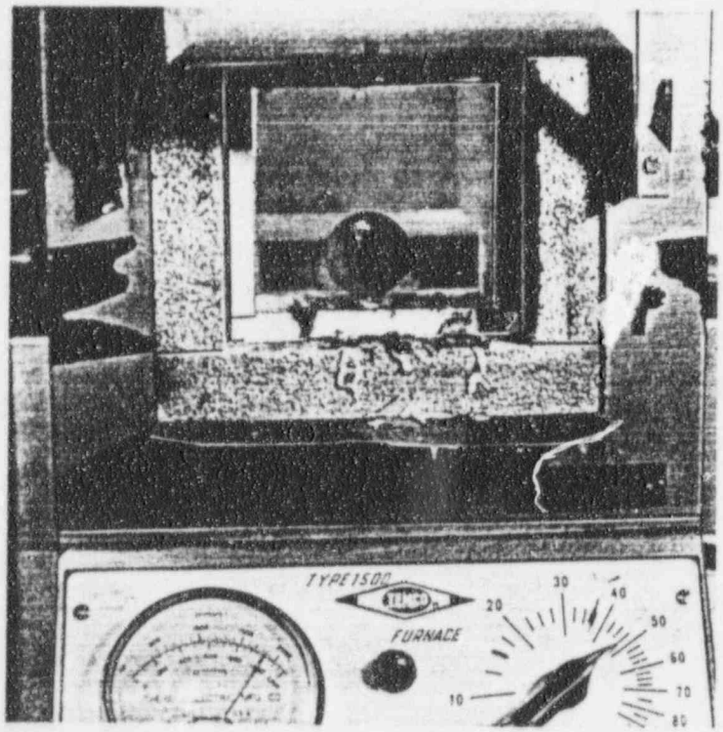
3M BRAND

RADIATION SOURCES

■ Having successfully developed the Radiating Microspheres, 3M's Nuclear Products Laboratory began developing a complete line of radiation sources. These sources, using 3M Brand Radiating Microspheres, are unlike ordinary sources; they offer you DOUBLE SAFETY. With the isotope securely caged in the microspheres and the microspheres safely sealed in corrosion resistant capsules, 3M makes the highest integrity sources available.



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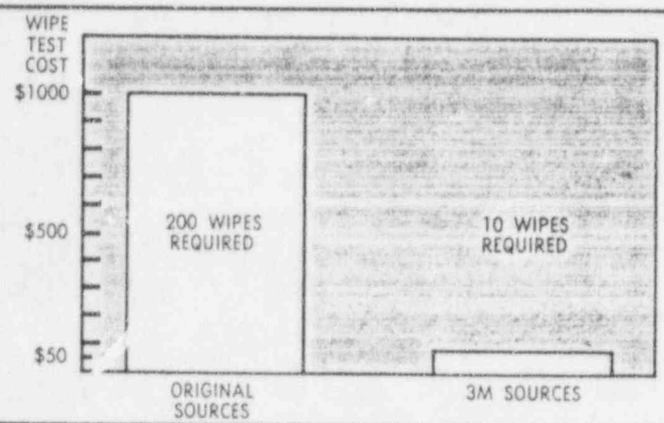

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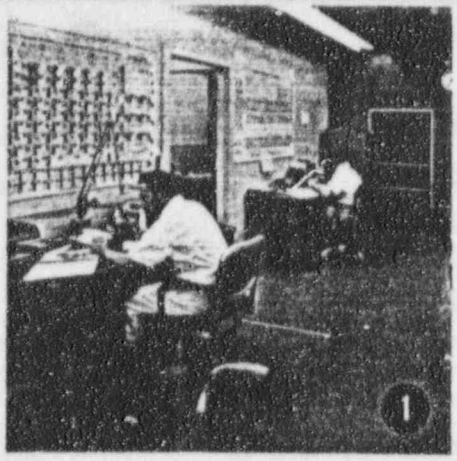

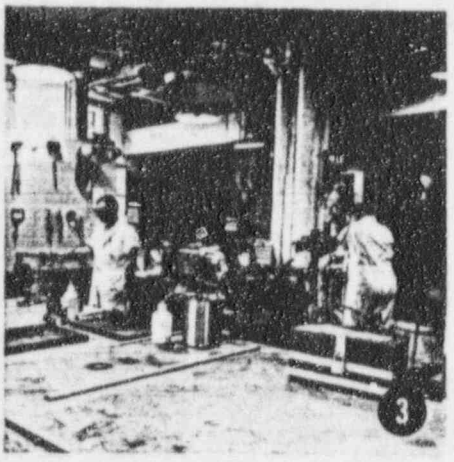

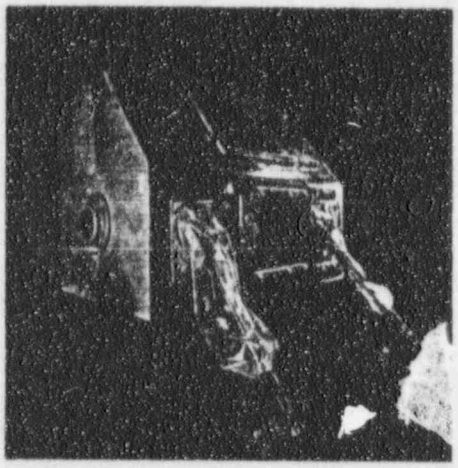

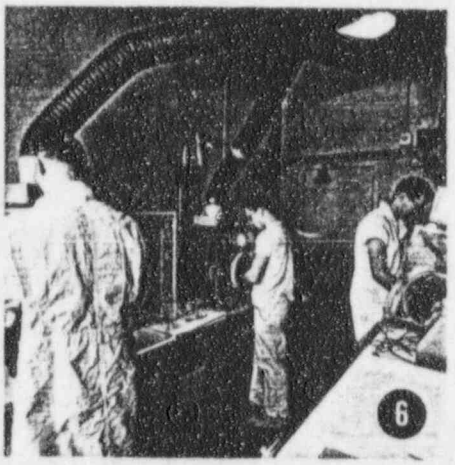

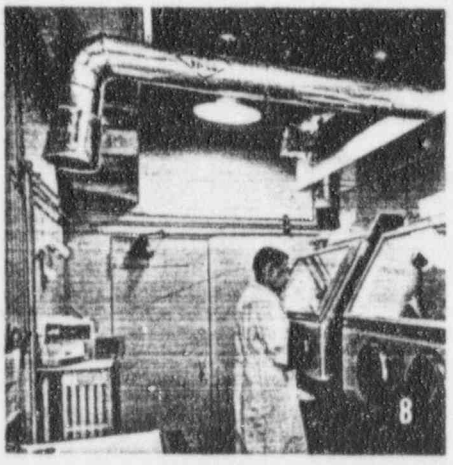

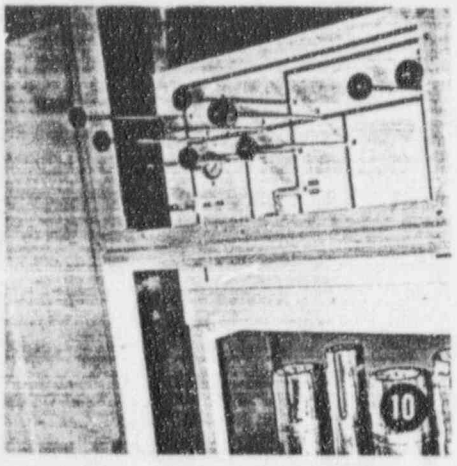

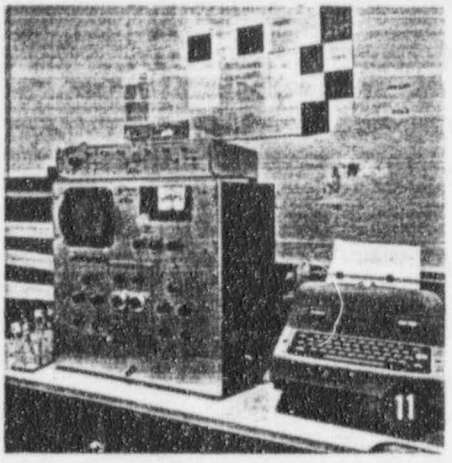

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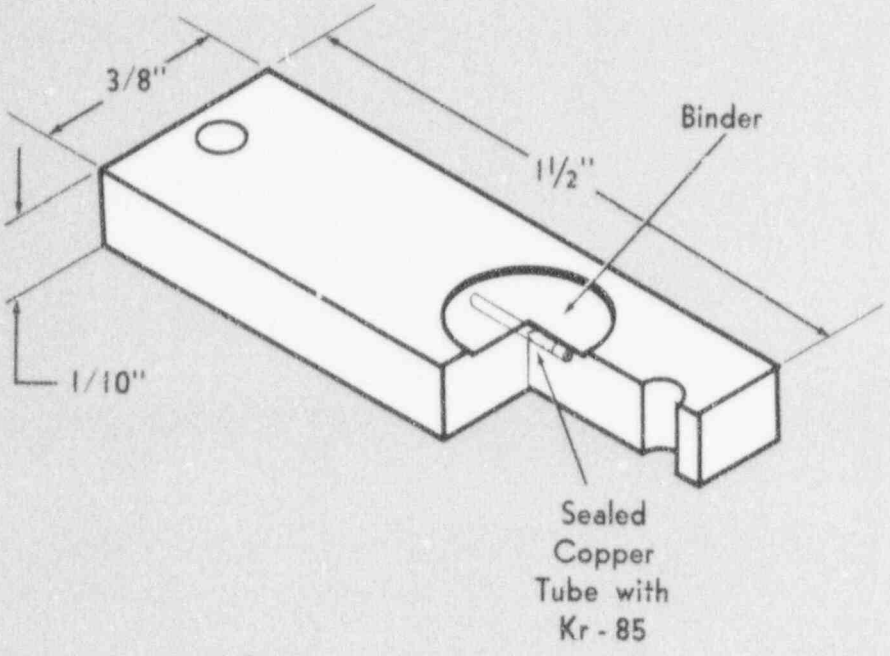
Nuclear Products 3M COMPANY

J-RRS-2(103.3)LP

POINT SOURCE KRYPTON 85



* NO WIPE TEST REQUIRED BY A.E.C.!

MODEL 3B4E

ISOTOPE:
HALF LIFE 10.6 YRS.

EMISSIONS:
BETA 0.67 MEV.
GAMMA 0.44 MEV. ½ %

BASE MATERIAL:
ALUMINUM

TYPICAL
APPLICATION

INSTRUMENT
CALIBRATION

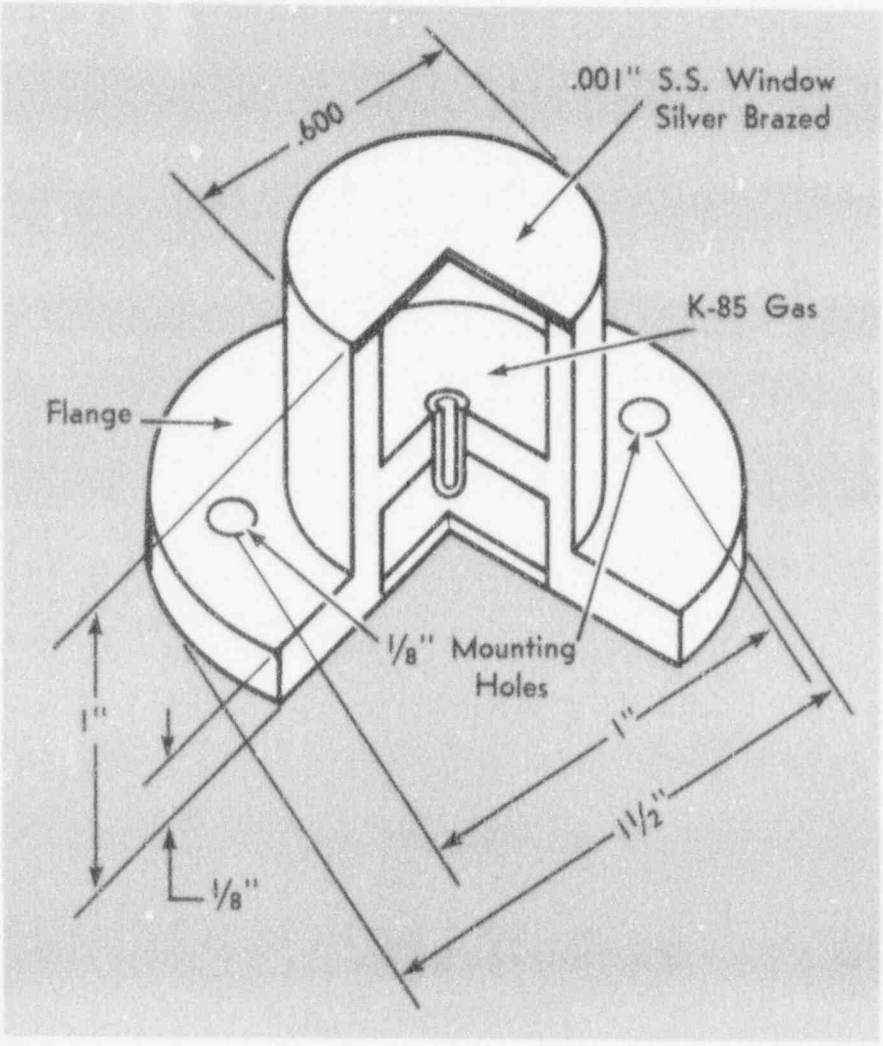
REFERENCE
SOURCE

NOMINAL CONTENT (mc)	UNIT PRICE IN LOTS OF			
	1 - 10	11 - 25	26 - 100	>100
0.001	$32	$28	$24	$18
0.01	34	30	26	20
0.1	36	32	28	22

3M Nuclear Products
MINNESOTA MINING & MANUFACTURING CO.
900 BUSH AVE. ST. PAUL, MINN. 55101 • TEL. 612-645-0321

3M BRAND

VOLUME SOURCE-KRYPTON 85



MODEL 3E4B

ISOTOPE:

HALF LIFE 10.5 YRS.

EMISSIONS:

BETA 0.67 MEV.

GAMMA 0.5 MEV. (0.5%)

MATERIAL:

STAINLESS STEEL

TYPICAL APPLICATIONS:

FLOWING FLUID DENSITY GAUGES

THICKNESS GAUGE

NOMINAL CONTENT (mc)	UNIT PRICE IN LOTS OF		
	1-4	5-9	10
100	$120	$110	$ 90
250	150	140	120
500	230	200	180
1000	330	280	250

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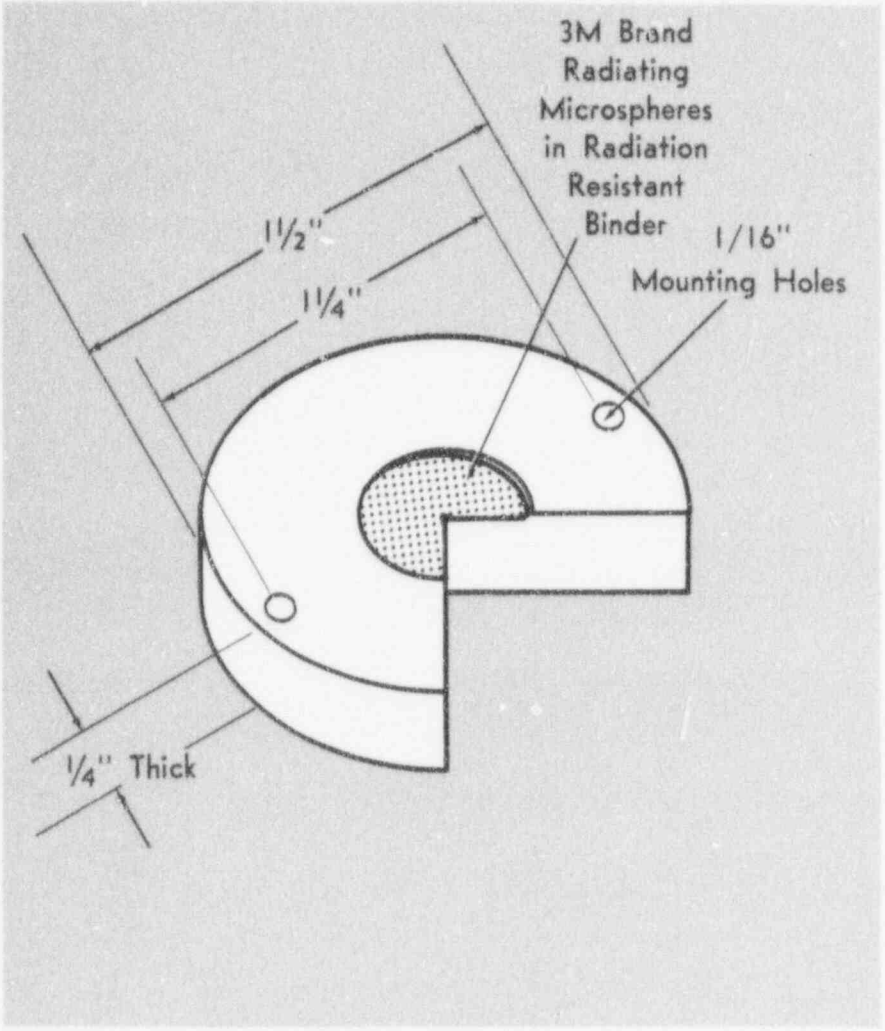
POINT SOURCE STRONTIUM-YTTRIUM 90



MODEL 3D1A

ISOTOPE:
HALF LIFE 28 YRS.

EMISSIONS:
BETA 0.61, 2.18 MEV.

BASE MATERIAL:
ALUMINUM

TYPICAL APPLICATIONS:
INSTRUMENT CALIBRATION
REFERENCE SOURCE

NOMINAL CONTENT (mc)	UNIT PRICE IN LOTS OF			
	1 - 10	11 - 25	26 - 100	>100
0.001	$31	$28	$23	$18
0.01	33	30	25	20
0.1	35	32	27	22

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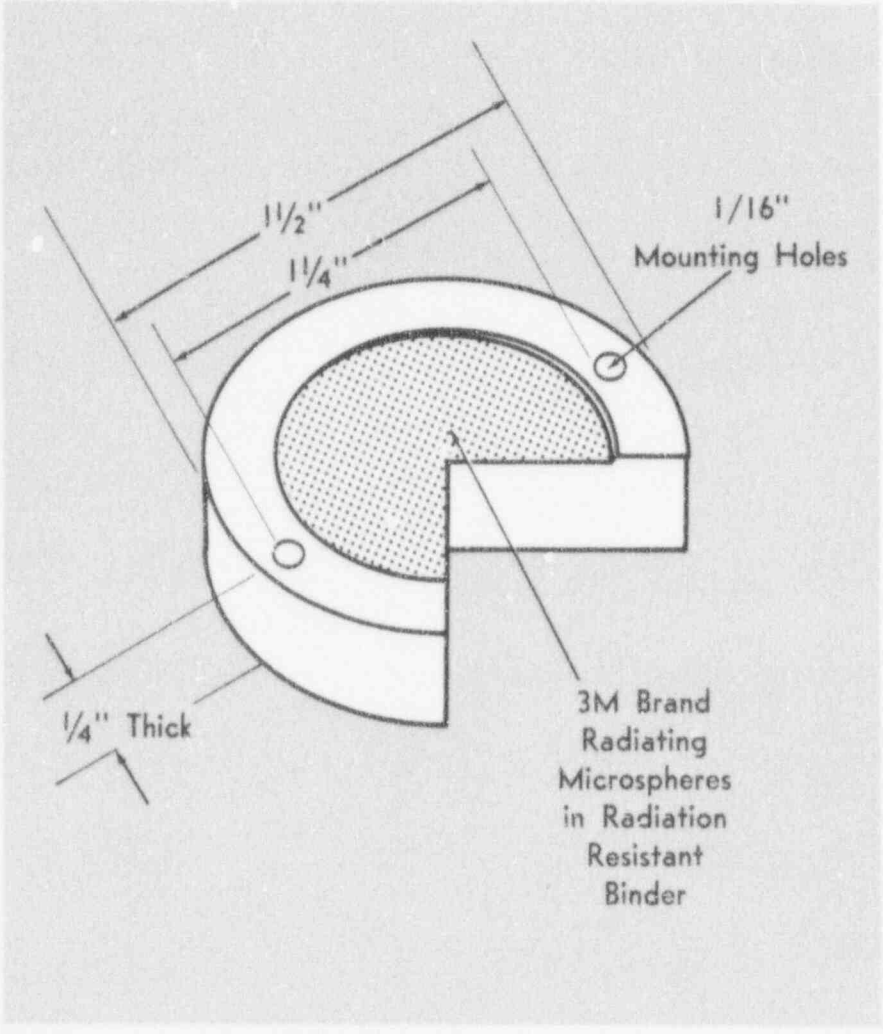
J-RRSI-3(103.15)R

AREA SOURCE POLONIUM 210



MODEL 2D8A

ISOTOPE:
HALF LIFE 138 DAYS

EMISSIONS:
ALPHA UP TO 5.3 MEV.

SOURCE BASE:
ALUMINUM

TYPICAL APPLICATIONS:
INSTRUMENT CALIBRATION
TEACHING AND
DEMONSTRATION

NOMINAL CONTENT (mc)	UNIT PRICE IN LOTS OF		
	1 - 4	5 - 9	10 OR GREATER
0.1	$100	$80	On Request
1	110	90	" "
10	120	100	" "

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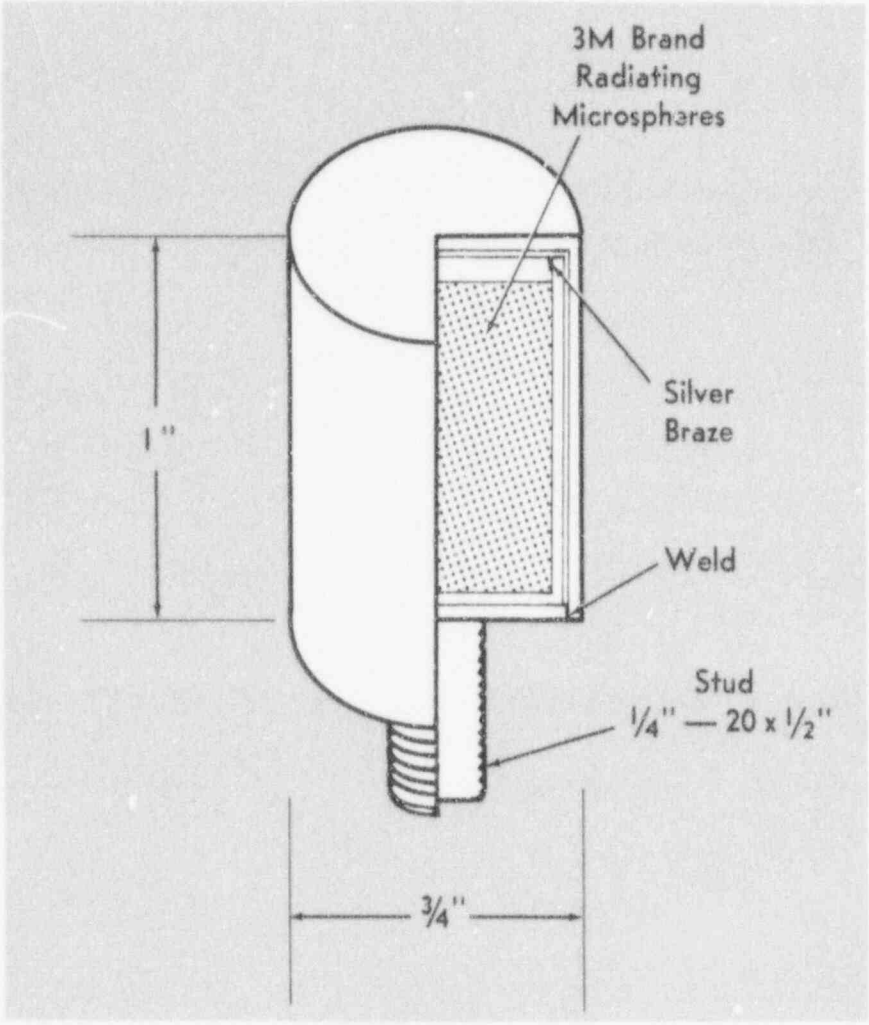
VOLUME SOURCE-CESIUM BARIUM 137



MODEL 4F6D

ISOTOPE:
HALF LIFE 30 YRS.

EMISSIONS:
GAMMA 0.66 MEV.

MATERIAL:
STAINLESS STEEL

TYPICAL APPLICATIONS:
LIQUID LEVEL GAUGES
FLOWING FLUID DENSITY GAUGES

NOMINAL CONTENT (mc)	UNIT PRICE IN LOTS OF		
	1 - 4	5 - 9	10 OR GREATER
100	$170	$155	$130
500	235	210	175
1000	340	300	250
2000	400	360	300

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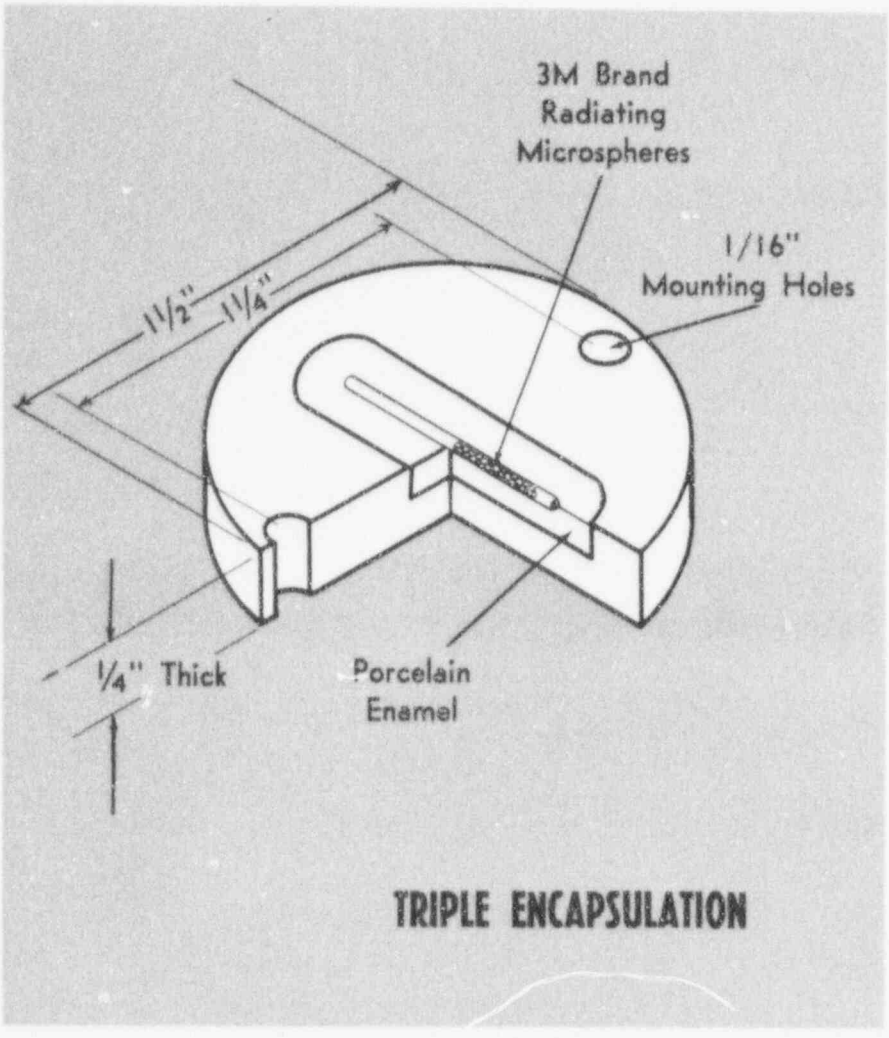
LINE SOURCE • STRONTIUM-YTTRIUM 90



TRIPLE ENCAPSULATION

MODEL 3A1F

ISOTOPE:

HALF LIFE 28 YRS.

EMISSIONS:

BETA 0.61, 2.18 MEV.

MATERIAL:

STAINLESS STEEL

TYPICAL APPLICATIONS:

BETA THICKNESS GAUGES

RADIATION DOSIMETRY

NOMINAL CONTENT (mc)	UNIT PRICE IN LOTS OF			
	1 - 10	11 - 25	26 - 100	> 100
0.1	$150	$140	$110	$ 90
1	160	150	120	100
10	175	160	135	110
50	190	175	145	120

OTHER SIZES AVAILABLE ON REQUEST.

3M Nuclear Products
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TECHNICAL DATA SHEET

"3M" Brand Radiating Microspheres

Minnesota Mining and Manufacturing Company
Nuclear Products Department
2301 Hudson Road
St. Paul 19, Minnesota

January 15, 1960

Description

"3M" Brand Radiating Microspheres herald a bold new approach to the utilization of radioactive materials.

The radioisotope is incorporated in the solid microsphere in such a way that the construction is chemically and physically inert, yet the useful radiation is allowed to escape. Leaching tests in 0.01 N HCl show that less than 0.01% of the activity is removed in 7 days. A great variety of isotopes, including alpha emitters, can be incorporated in the microspheres at almost any desired level of activity.

The principal hazard of products containing alpha or beta emitting isotopes is the internal radiation attending the accidental ingestion or inhalation of the isotope. Incorporating the isotope in "3M" Brand Radiating Microspheres before fabricating the product reduces this internal hazard to a minimum.

Table I contains a list of some of the more important isotopes that are available in "3M" Brand Radiating Microspheres. Virtually any isotope can be incorporated in the microspheres.

Table I

Examples of "3M" Brand Radiating Microspheres

Isotope	Type of Radiation	Half-Life	Estimated Upper Limit of Specific Activity
Ba-140-La-140	β,γ	12.8 days	10^4 curies/gm.
Calcium-45	β	163 days	100 millicuries/gm.
Cerium-144	β,γ	282 days	100 curies/gm.
Cesium-137	β,γ	30 years	10 curies/gm.
Chromium-51	γ	27.8 days	5 curies/gm.
Cobalt-60	β,γ	5.3 years	5 curies/gm.
Nickel-63	β	85 years	20 millicuries/gm.
Promethium	β	2.6 years	30 curies/gm.
Polonium-210	α	138 days	10^3 curies/gm.
Radium-226	α,β,γ	1622 years	0.3 curies/gm.
Scandium-46	β,γ	85 days	10 curies/gm.
Silver-110	β,γ	270 days	100 millicuries/gm.
Strontium-90	β	28 years	12 curies/gm.
Thallium-204	β	4.0 years	1 curie/gm.
Yttrium-90	β	61 hours	10^5 curies/gm.

Properties of Microspheres:

Color: Milky white

Size: For usual application - 60 microns; but can be obtained in carefully graded sizes from 10 to 100 microns

Density: Absolute - 4.0 gm./cm^3

Bulk - about 2.0 gm./cm^3, depending on size

Melting Point: 1500° C.

Solubility: Less than 1 part per billion in salt water or dilute acid (100 ml. of test solution -- time of test one week).

Radiation Stability: Greater than 10^9 Rads (no visible change nor any decrease in the retention of the isotopes at this dose).

Hazard Evaluation

Internal:

The incorporation of a radioisotope into "3M" Brand Radiating Microspheres prevents that isotope from behaving in a normal metabolic way. For example, work at 3M has shown that when Sr-90 microspheres were fed to rats, no detectable amount of radioactivity was deposited in the carcass of the animal (less than 0.0007% of the amount fed). Therefore, the level for ingestion of Sr-90 carrier to give a body burden of 1 μc, the presently accepted maximum, would be many times the level of soluble Sr-90 which could be tolerated. As an example, if we assume the same conditions to exist in man as in the rats mentioned above, when less than 0.0007% of the dose was in the carcass after four days, one could ingest at least 140 mc of Sr-90 carrier and still not exceed the 1 μc body burden.

External:

The usual precautions must be taken to shield the external radiation. A report entitled "Hazard Evaluation of Pm-147 Activated Self-Luminous Devices Made with '3M' Brand Radiating Microspheres" is available upon request.

Applications

A) Self-luminous devices - clocks, watches, instrument dials, panels, signs, flash lights; detailed information on any particular self-luminous application is available upon request.

B) radiation sources (alpha, beta, gamma, X-ray, transmitting) -- industrial gauging, calibration sources, static eliminators, extended planar sources, detector sources for gas phase chromatography.

Since 3M Brand Radiating Microspheres are ceramic material themselves, they can easily and safely be incorporated into ceramic matrices to give radioactive sources which are physically stable at temperatures in excess of 1000° C. A great variety and amount of isotopes can be incorporated in the microspheres.

The matrix body can be practically any ceramic powder which can be pressed or cast and sintered into a strong, useable piece. The 3M Brand Radiating Microspheres (containing the desired radioactivity) can be incorporated directly into the ceramic matrix, or they can be fixed in place by a high temperature, inorganic cement.

Radioactive Sr-90 sources made using the inorganic cement method, have shown negligible losses of activity in conventional wipe tests (less than 10^{-5}%) even after being heated to 500° C. Wipe tests of specimens loaded with Sr-90 and heated to 1000° C. removed only 10^{-3}% of the activity. The microsphere sources are inert to common organic solvents such as carbon tetrachloride and acetone, as well as water and most dilute acids.

Metal sources can also be fabricated by powder metal techniques if the end use has a low temperature requirement but needs greater mechanical strength and shock resistance.

C) Medical -- isotopes of almost any energy and half-life can be selected for such radiation therapy devices as needles, plaques, etc., -- or direct internal use.

Again, it must be stressed that the likelihood of a system using Pm-147 returning to earth intact is extremely remote. The docking target is part of the LM, which is scheduled to remain in lunar orbit. Nevertheless, if the LM did reenter the atmosphere, the probability that the system will remain intact is extremely small. It is virtually impossible for the docking target to reenter and remain intact to impact on land.

However, if all these conditions were satisfied and an individual were to chance upon the intact system and found a use for it, a continuous contact with a disc for 1,000 hours would be required to achieve a dose that would do no more than blister the skin if the total dose were received in 24 hours. Over 1,000 hours would also be required to achieve a "deep dose" equivalent to one that would produce a detectable blood count change only if the total dose were received in 24 hours. Hence no credence can be given to the possibility of a significant exposure.

5.2 INDIVIDUAL SOURCES

5.2.1 Self-Luminous Disc

The discs (3M Model 1E2J) are composed of fused silica which has a melting temperature >2700°F. If protected by surrounding structure through most of the reentry heating, some discs may impact as individual units.

The silica is thick enough to absorb the Pm-147 beta completely; only the gamma and bremsstrahlung radiation is detectable at the surface of a disc. The radiation from a disc was determined by 3M Corporation to have a peak intensity energy of about 45 Kev (see Figure 20). The percentage of transmission of 45 Kev X-rays through various thicknesses of material is shown in Table 7. Table 8 gives the dose rate as a function of distance from one disc containing 300 mc of Pm-147. The values were measured by 3M Corporation with a GM tube survey meter.

TABLE 7*

PERCENTAGE OF TRANSMISSION OF 45 KEV X-RAYS THROUGH VARIOUS MATERIALS

Thickness (in)	Plastic	Aluminum	Steel	Lead
0.125	93	71	0	0
0.25	86	51	0	0
0.5	75	26	0	0
1	56	7	0	0

TABLE 8

DOSE RATE VERSUS DISTANCE FROM ONE DISC CONTAINING 300 MC OF Pm-147

Distance (in)	Dose Rate (mr/hr)
2	15
3	10
6	3
12	1
24	0.4

* NBS Circular 583 (Supplement), X-ray Attenuation Coefficients from 10 Kev to 100 Mev, 1959.

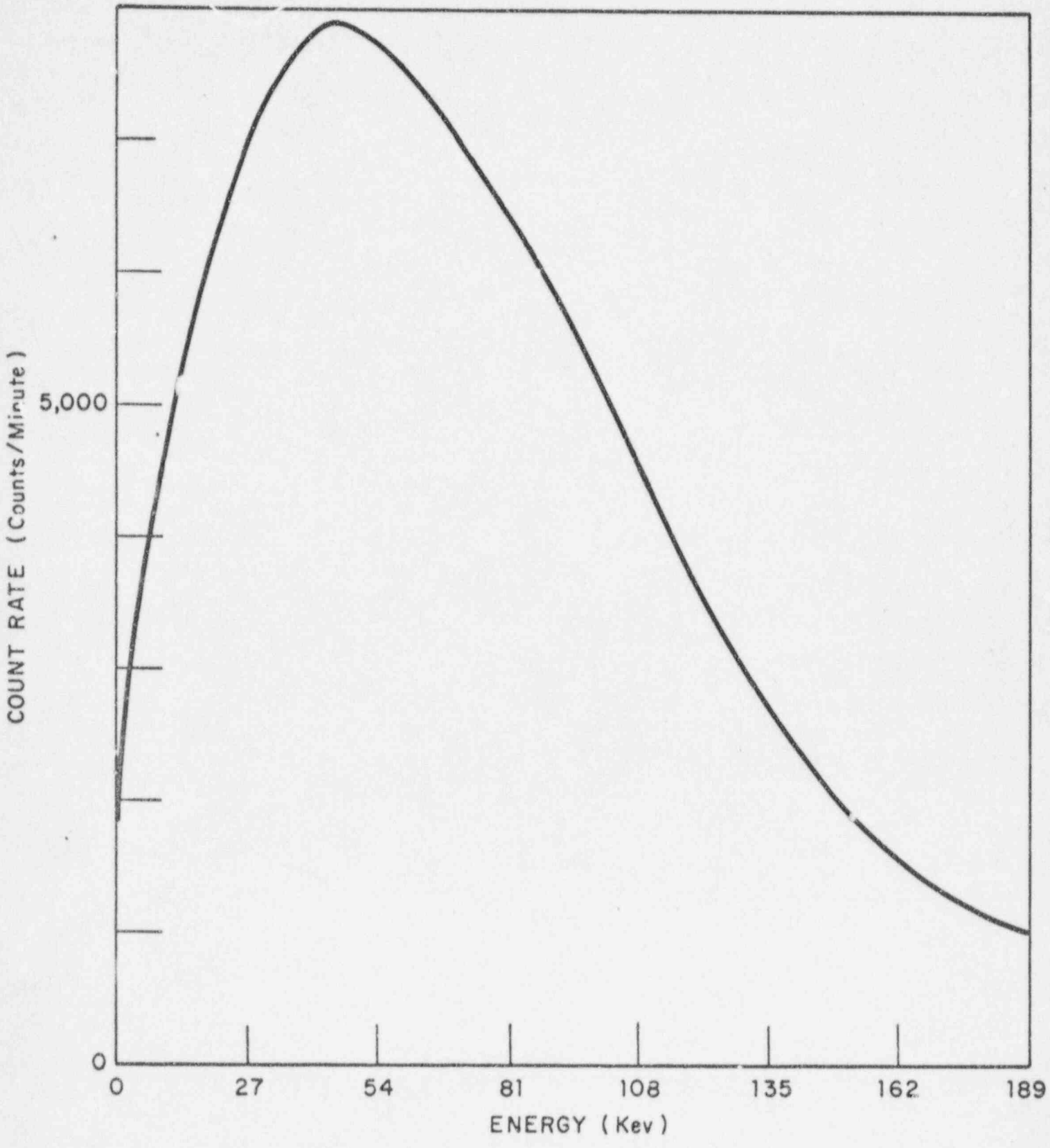

FIGURE 20 Pm-147 GAMMA AND BREMSSTRAHLUNG RADIATION SPECTRUM FOR NUMBER 7 DOCKING TARGET

The MSC Health Physics Group measured the dose rates at several points about the disc. These dose rates were measured with three different instruments:

1. TLD (Thermoluminescent Dosimeter)
2. Technical Associates Cutie Pie
3. Victoreen 188 Condenser Chamber

Table 9 lists the dose rates as measured by each instrument.

TABLE 9

DOSE RATE FROM ONE LUMINOUS DISC
CONTAINING 300 MC OF Pm-147

	Distance (inches)	TLD (mr/hr)	TA-CP (mr/hr)
Front Surface	Contact	860	650
	1	--	8.6
	2	--	3.9
	3	5.6	2.3
	4	--	1.8
	5	--	1.1
	6	1.4	0.7
	12	0.4	--
	24*	--	--
Back Surface	Contact	510	568
	1	--	10
	2	--	4
	3	--	2.5
	4	--	1.6
	5	--	1
	6	--	0.7
Side	3	1.6	--
	6	0.2	--

* Victoreen 188 CC read 0.03 mr/hr

Table 10 consolidates the measured dose rate data available at this time.

The spread between measurements at identical distances up to 6 in. is not considered discouraging. Since the Victoreen R-chamber is relatively less sensitive at 24" than the GM meter, due to the lower average energy of the radiation at that distance, the actual radiation level at this distance is considered to be closer to the GM meter reading.

The data for the dose rate from a disc was plotted on log-log graph paper as a function of distance. If the data are accurate and the disc does indeed constitute a point source, the data should form a straight line plot with a slope of 2. Each set of data points departed from this ideal, but the TLD data curve came closest to being a straight line and this curve did have a slope of 2. This, added to the fact that the TLD measurements in all cases fell between the GM measurements and the Cutie Pie measurements, tends to indicate the TLD data are mutually consistent. On the basis of best fit to measured data, a "best estimate" of each real value was made. These values are presented in the last column of Table 10.

TABLE 10

COMPOSITE OF MEASURED DOSE RATES
FROM ONE LUMINOUS DISC

Distance (inches)	MSC TLD (mr/hr)	MSC TA-CP (mr/hr)	MSC Victoreen 188 (mr/hr)	3M (GM) (mr/hr)	Best Estimate (mr/hr)
Surface	860	-	-	-	860
2	-	4	-	15	14
3	5.6	2.3	-	10	5.6
6	1.4	0.7	-	3	1.4
12	0.4	-	-	1	0.4
24	-	-	0.03	0.4	0.1

Another possibly valid rationale for considering the TLD measurements most reliable stems from the observation that the physical size of the TLD detector is small in comparison with the size of the disc. (The detector size of the TLD is 0.5 in. diameter by 0.015 in. thick.) Since the TLD data represents a good fit for the best estimate for dose rates at distances greater than 2 in., the TLD data were used as a measurement of the surface dose. Calculations of the radiation resulting from a Pm-147 luminous disc are complicated and would require many hours of computer programming and data evaluation. Since the measured values confirm that the levels are low, it did not appear to be productive to carry out a sophisticated analytical computation. However, at some future time when perhaps larger sources need to be considered, such an analytical evaluation may be required. This may be particularly desirable when the radiation interface between a radiation sensitive experiment or measuring equipment and the stray radiation from a radiation source must be analyzed.

Much more credible than any of the postulated intact returns to earth of systems is the possibility that an intact disc would survive reentry. However, the small size of the disc (0.6 in. diameter) combined with the unlikely eventuality that the disc would come down on land renders the probability of a disc coming into an individual's possession a very remote statistical possibility. If all the conditions were satisfied a disc might be regarded as an object suitable for wearing as an amulet or adornment (aborigines, bellydancers, etc.). A constant skin contact of several thousand hours (more than 4 months) would be required to produce a dose equivalent to that required for a biological effect if such a dose were received within 24 hours.

5.2.2 Switch Tips

The switch tips (approximately 130) contain a total of 617 mc of Pm-147.

Each unit has 2-6 mc of Pm-147 (as 3M Brand Radiating Microspheres) mixed with phosphor and a binder in a clear plastic (methyl acrylate) switch tip.

The procurement specifications require that the total radiation shall be no more than 5 mr/hr at 1 cm, and 1.5 mr/hr at 5 cm. Production models typically emit 1-3 mr/hr at 1 cm and 0.2-0.5 mr/hr at 5 cm. Table 11 gives typical dose rate values at various distances, as obtained from information provided by the 3M Corporation.

TABLE 11

DOSE RATE VERSUS DISTANCE
FROM ONE SWITCH TIP CONTAINING 5 MC OF Pm-147

Distance (inches)	Dose Rate (mr/hr)
Contact	10
0.4	2
2	0.3
4	0.08
6	0.03
12	0.01

If the switch tips were positioned in such a manner that they were all located at a single point, the total dose rate at one foot would be about 1 mr/hr. In reality the total dose rate from all switch tips will be considerably less since the geometry that could cause the 1 mr/hr dose rate is impossible.

Switch tips are installed in the LM, and the likelihood of the LM returning to solid earth intact is highly improbable. However, as was the case for the discs, if credulity were strained sufficiently, a situation might be imagined wherein a switch tip found favor in someone's eyes and used as an adornment. An exposure of over 300 years would be required to produce a dose equivalent to that which produces a detectable effect if received in 24 hours. Therefore the question of biological significance can be completely discounted.

5.2.3 Microspheres

The form of radioluminescent material that most probably could interact with the biosphere (man and his immediate environment) is the individual microsphere. While it has been shown in Section 4.4 that the probability of even a single microsphere finding its way into man is very small, the biological significance of this extremely remote occurrence can be evaluated by calculating the radiation exposure resulting from the deposition of a microsphere on the skin and the exposure resulting from the ingestion or inhalation of a microsphere.

External Exposure - A microsphere may cause an individual to experience a skin dose. The maximum range of a 0.22 Mev beta particle is about 50 mg/cm^2. This corresponds to about 500 microns of tissue.

The microsphere is small in comparison with the range of the Pm-147 beta particle and therefore to analyze the maximum potential exposure rate, the small amount of absorbtion within the microsphere was ignored. No problem can result from energy absorbed by dead tissue. In a human, the surface layer of dead tissue is considered to be about 70 microns thick, and the tissue dose at this depth becomes the controlling factor.

A computer program was set up to calculate dose rates at 5 microns increments, out to 500 microns. The results are presented in Table E-4 of Appendix E. The amount of activity in a single microsphere has a nominal value of 0.1 μc. With this quantity, the tissue dose rate at 70 microns is 1160 rads/hour.

This value is the dose rate at a point directly under the microsphere and at a depth of 70 microns. The proper value is that taken over a skin area of about one square centimeter. Computation of this value was also performed by computer for several values of depth and area. For 70 microns depth and an area of 1 cm^2 (radius of 5650 microns), the averaged dose rate value is 0.24 rads/hr. If the area at this depth is reduced to about 500 microns (corresponding to the range of the maximum energy beta-particle), the averaged dose rate value increases to 32 rads/hr.

Recent experiments with uranium-carbide microspheres performed at LASL have shown that integrated doses of up to 50,000 rads to a small area of monkey skin have resulted only in a reddening of the skin without permanent damage. These doses are point doses at 100 microns depth. By comparison, the computed dose rate for a single microsphere at 100 microns is 400 rads/hr or 67,000 rads per week.

NCRP Report Number 29, "Exposure to Radiation in an Emergency", lists the maximum beta radiation required to produce recognizable injury to the skin of a pig. About 20,000 rads to the skin surface or about 1,200 rads at 1 mm depth (maximum beta energy of 0.17 Mev) was required. These results compare favorably with those at LASL.

Internal Exposure - A microsphere could enter the body with water or food. The microsphere would enter the stomach and pass into the intestinal tract with the food.

Most of the beta energy will be absorbed by the contents of the stomach or the intestinal tract, but since the microsphere may be adjacent to the lining, and to be conservative in this analysis, it is assumed that no absorption occurs in the contents.

An analysis* was performed of ingestion of insoluble radioactive material where some portion of the GI tract is the critical body organ. The organs considered in the GI tract are listed in Table 12.

* Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955, Volume 13, page 139.

TABLE 12 PHYSIOLOGICAL PARAMETERS OF GI TRACT

GI Tract Organ	Mass (grams)	Effective Radius (cm)	Residence Time (hours)
Stomach	250	10	1
Small intestine	1100	30	4
Upper large intestine	135	5	8
Lower large intestine	150	5	18
			Total = 31 hours

In the case of Pm-147, the long half-life of 2.6 years and the lack of any radioactive daughters of importance greatly simplifies computation of the single exposure values of maximum permissible intake (MPI) for ingestion of insoluble radioactive material when the GI tract is the critical body organ. These values of MPI in microcuries will deliver 0.3 rem to the indicated organ during movement through the GI tract. Values for Pm-147 are listed in Table 13, column 2, for each of the four organs.

TABLE 13 MPI AND RADIATION DOSE TO GI TRACT

GI Tract Organ	MPI for 0.3 rem (μc)	Dose from 0.1 μc Microsphere (millirem)
Stomach	1700	0.029
Small Intestine	1800	0.027
Upper Large Intestine	110	0.44
Lower Large Intestine	56	0.88

The values indicate that the large intestine receives virtually the total dose of less than two mrem.

The accepted maximum size of respirable particles is about 10 microns. Most of the microspheres (20 ± 10 micron diameter) are therefore too large for inhalation. The natural rejection mechanism in the bronchial tubes and the lungs, the cilia, sweep large particles out into the throat to be swallowed and to enter the digestive tract.

In addition to the particle size distribution inherent in their manufacture, there is also a possibility that some of the larger microspheres withstand reentry heating in a partially ablated condition. As a result, a microsphere may have diminished enough in size to enter the lungs and remain there as an insoluble particle.

For the purpose of maximum exposure estimates, all of the 0.1 μc activity is assumed to be centered on a particle small enough (< 10 microns) to enter the lungs. For this condition, the integrated dose to the lung is only 55 mrem (see Appendix E). This has no biological significance.

5.3 SUMMARY

The only system that, with any degree of credibility, can be postulated as returning to earth intact, is the docking ring and this unit is mounted on the forward heat shield which is jettisoned during reentry. Because of the position of the docking ring on the CM, the self-luminous discs of the ring are not subjected to temperatures that could possibly cause their disintegration. The possibility of contamination of the CM as a result of disintegration of Pm-147 containing self-luminous discs can therefore be eliminated. The possibility of the heat shield impacting on land and causing a biologically significant exposure is a barely credible statistical possibility.

If the luminescent discs separated from the docking ring, a theoretical possibility that one or more would survive must be considered. But such discs would be randomly distributed over an area of some 500 by 3000 nautical miles. In addition, all precautions have been taken to ensure that the spacecraft and all other component debris will impact in the ocean. Therefore the probability of a single disc falling into the hands of a person ignorant of its nature is so remote that it can be discounted.

There remains the theoretical possibility that a single microsphere would land on or be inhaled or ingested by a human. No biological significance can be attached to any of these eventualities.

If the incredible aspects of all the above postulated events were to be discounted and incredibility were turned into credibility, certain total dose values could be calculated that could of themselves produce a measureable biological effect. However, the single most important factor of these exposures is that a very long exposure time (hundreds or thousands of hours) is required to receive such an exposure. The biological end point chosen was a moderate erythema from a "surface dose" and a detectable (but meaningless) change in blood count from a "deep dose". The exposure time for both of these end points is 24 hours. A similar dose received over a much longer time cannot produce the same end point due to the inherent recovery aspects of the tissue and cells under consideration. The exposure postulated as producing a detectable effect within a 24-hour exposure period becomes biologically insignificant when the same dose is received over a long period of time. Thus, no credible situation can be postulated where the exposure that might be received from the self-luminous sources currently planned for Apollo can be considered of biologic significance.

CONCLUSIONS

One general conclusion is of overriding importance; the use of Pm-147 microspheres in self-luminous discs cannot, under any credible circumstances, cause exposures of biological significance.

This general conclusion is supported by examination of 1) reentry trajectory characteristics of returning spacecraft components and 2) radiation mechanisms resulting from programmed or random return to earth of Pm-147 containing systems or modules.

The analyses related to the trajectories of the CM, SM or LM were performed taking into consideration situations that tax the imagination. Similarly the circumstances attending the possible radiation exposures that were postulated required the inclusion of eventualities so exotic as to appear ridiculous.

The fundamental reason why the use of Pm-147 in the systems described is deemed feasible is that the exposure times required to receive biological significant doses far exceed the time limits within which such exposures must be received in order to cause detectable biologic effects.

APPENDIX A

DESCRIPTION OF APOLLO PROGRAM SELF-LUMINOUS SOURCES

A.1 RADIATING MICROSPHERES

All of the radioactive material systems discussed in this report contain 3M* Brand Radiating Microspheres. The microspheres are made by sorbing Pm-147 throughout a porous, microspherical, inorganic ion exchanger and then fixing them by a heat treatment. The amount of impurities, consisting of Pm-146, Pm-148, Eu-152, and Eu-154 in a sample of Pm-147 as received by 3M Corporation is less than 10^{-4}%, as measured by ORNL. Following fixation, the microspheres are washed with strong mineral acids to remove any loosely bound activity.

The microspheres have a ceramic matrix and are physically insoluble in most organic and inorganic solvents, concentrated acids or alkalies, or even aqua regia at 100°C or higher. They are very tough and resist breaking under normal circumstances. Extensive soak tests indicate that less than 0.01% of the Pm-147 will be leached from the microsphere during the first 24 hours of soaking. The leaching rate after this period decreases with time. The physical properties of the microspheres are presented in Table A-1.

TABLE A-1

3M BRAND MICROSPHERES PHYSICAL PROPERTIES

Matrix Material	Ceramic
Color	Milky White
Melting Temperature	>1500°C (2700°F)
Diameter	20 ± 10 microns
Absolute Density	3 g/cm^3
Bulk Density	2 g/cm^3
Activity	10 c/gm
Specific Activity	0.1 μc/microsphere

A.2 SELF-LUMINOUS DISCS

The radiating microspheres discussed in Section A.1 contains the Pm-147 used in the self-luminous discs. The discs (3M model 1E2J) are fabricated from fused silica, have a density of approximately 2.5 and a melting temperature of >2700°F. Each self-luminous disc contains 300-1000 mc Pm-147 in 3M Brand radiating microspheres mixed with a phosphor. (A maximum of 1 c Pm-147 per disc has been approved for licensing by the AEC, according to 3M Company.)

The ceramic housings are machined from Corning #7940 Fused Silica. When received from the manufacturer the blanks are examined to be free of scratches, excessive bubbles, and to be optically transparent. After machining the dimension tolerances are as follows:

Dimension	Acceptable Values (inches)
Outside Diameter	0.62 - 0.64
Inside Diameter	0.49 - 0.51
Outside Thickness	0.185 - 0.195
Window Thickness	0.05 - 0.07

All ceramic housings not meeting these dimensional requirements are rejected. Figure A-1 is the specification control drawing for a disc.

One of every 100 rough discs is submitted for analysis. The disc is decomposed with 47% HF to produce SiF_4. The volatile SiF_4 is removed by ignition and the residue examined. The residue must be less than 1% by weight of the original sample, otherwise the entire batch of housings will be rejected.

The phosphor used has a chemical composition of ZnS:Ag:Cu. It has a peak wave length of 5200 A, which is in the green portion of the visible spectrum.

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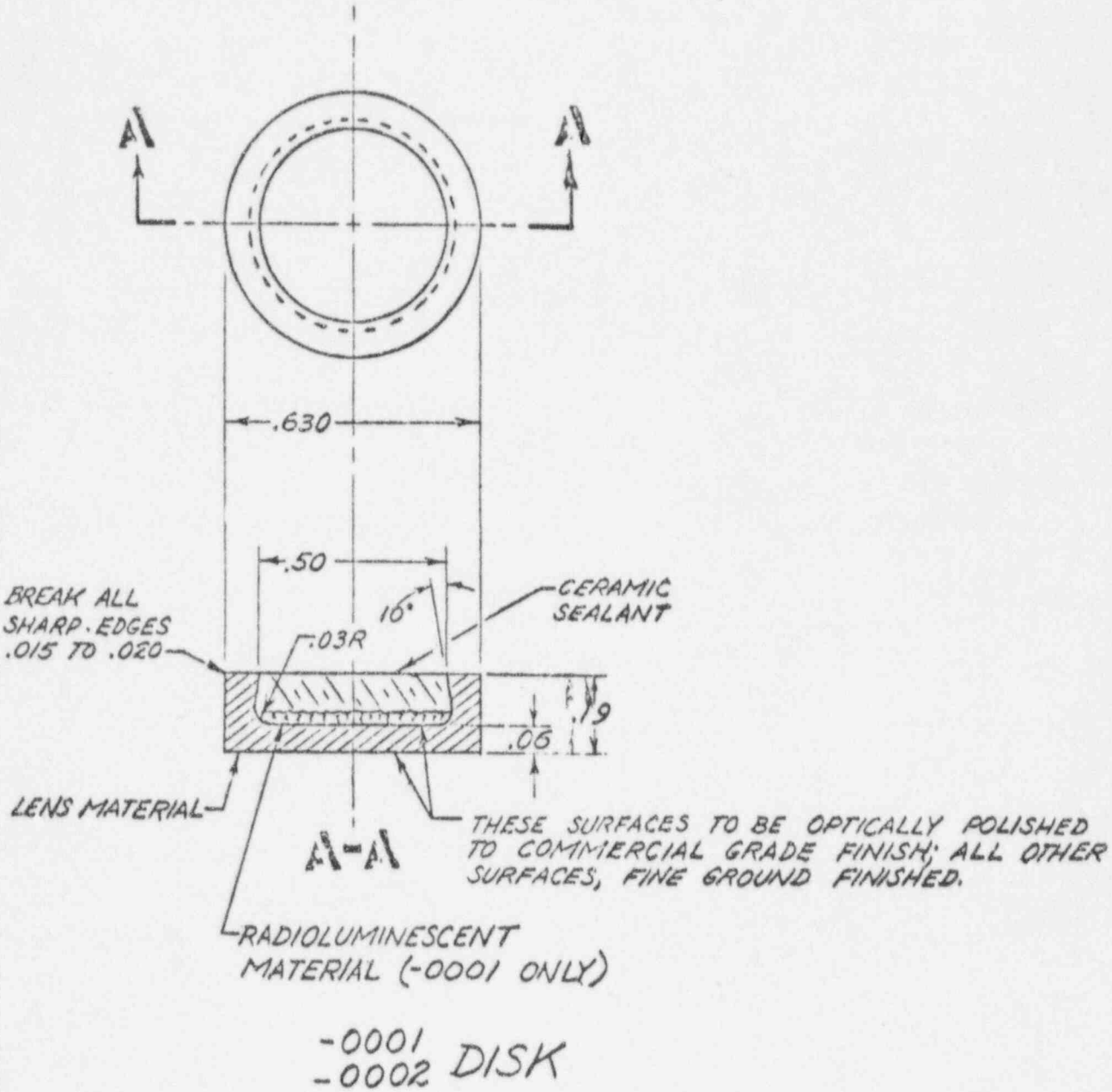
* Minnesota Manufacturing & Mining



-0001
-0002 DISK

FIGURE A-1

REVISED

TOLERANCES, EXCEPT AS NOTED ANGLES ±30' DECIMALS .XX = ±.03 .XXX = ±.010	TOLERANCES ON HOLES NOTED "DRILL"	.013 THRU .040 : +.001 −.001 .041 THRU .130 : +.002 −.001 .131 THRU .229 : +.003 −.001 .230 THRU .500 : +.004 −.001	.501 THRU .750 : +.005 −.001 .751 THRU 1.000 : +.007 −.001 1.001 THRU 2.000 : +.010 −.001	CODE IDENT NO. 03953	
DR BY T. SCOTT SMITH 7 MAR 66	NORTH AMERICAN AVIATION, INC. SPACE and INFORMATION SYSTEMS DIVISION 12214 LAKEWOOD BLVD. DOWNEY, CALIFORNIA			CONTROL PART	
CHK BY					
APPD	7-17-66	DISK, RADIOLUMINESCENT (SPEC CONTROL DRAWING)		ME 434-0052	
APPD	7-17-66			SHEET 1 OF 3	

The binder which holds the phosphor and microspheres together is a solution of $K_2O:SiO_2$ in water.

The self-luminous paint consists of the following mixture:

6.5 - 7.5 parts (weight) of phosphor
2.0 parts (weight) of binder
0.5 - 1.5 parts (weight) of microspheres

Approximately 0.25 g of the paint is deposited in the center section of each disc. This is cured for 1-1/2 hours at room temperature, followed by 1-1/2 hours at 127°C.

The open end of the hole in the disc blank is sealed with a ceramic sealant which consists of 99.8% SiO_2 in a solvent. After leveling, this is air-dried at least four hours at room temperature followed by 1-1/2 hours at 127°C. The hole is slanted such that the ceramic sealant plug cannot slip out of an intact disc under any condition.

Each disc is thoroughly inspected prior to acceptance. These tests include the following:

Visual Inspection	Brightness
Dimensional Inspection	Initial Wipe Test
Weight	7 Day Wipe Test

The visual inspection checks the paint for dark spots, blotches, gaps or excessive bubbles. Sloppy workmanship of any nature is also noted at this time.

The dimensional inspection checks the outside dimensions of each disc. The maximum weight for any disc is 2.5 g. The brightness test checks to see that the light from each disc is at least 1 foot lambert.

The initial and the 7-day wipe tests are designed to detect any removable contamination. This is done by wiping all available surfaces with a filter paper wipe and analyzing the wipe. Sources with more than 0.005 μc of removable activity are discarded as radioactive waste.

The discs have excellent resistance to ordinary weathering and to attack by nearly all chemical reagents. Rapid attack occurs only on exposure to hydrofluoric acid or concentrated alkaline solutions, the rate of attack increasing with elevated temperature. Table A-2 lists the chemical durability of fused silica to three typical reagents.

TABLE A-2
CHEMICAL DURABILITY OF FUSED SILICA

Reagent	Temperature (°C)	Surface Erosion (Inches)
5% HCl (24 hrs)	95°	1×10^{-6}
Water (24 hrs)	100°	5×10^{-7}
5% NaOH (24 hrs)	95°	5×10^{-4}

A.3 SELF-LUMINOUS SWITCH TIPS (SLST)

Each toggle switch with SLST in the LM control panel contains 2-6 mc of Pm-147. The activity is contained in the 3M radiating microsphere (see Section A.1 of this Appendix). A phosphor and a binder (Epo-Lum 100) are mixed and imbedded in a hole in the switch tip. The switch tip end is then covered with a clear plastic (methyl acrylate) and sealed with Maraglas Resin #655. *

The body of the switch tip, methyl acrylate, is very resistant to radiation damage with only slight darkening occurring at absorbed doses of 100 megarads.

Procurement specifications require that the total radiation from the switch tips not exceed:

a) 5 mr/hr at 1 cm from surface
b) 1.5 mr/hr at 5 cm from surface

Production models typically emit:

a) 1-3 mr/hr at 1 cm
b) 0.2-0.5 mr/hr at 5 cm.

* Product of Marblette Corp.

APPENDIX B

FLIGHT QUALIFICATION TESTS

B.1 SELF-LUMINOUS DISCS

Test	Conditions	Results
1. Humidity	40-100°F at humidities to 100% for two days	<0.001 μc Pm-147 detected on wipe test ∴ passed
2. Shock	Total of 18 shocks having a 50 g peak with a sawtooth pattern (11 ± 1 millisecond rise, 1 ± 1 millisecond decay)	<0.001 μc Pm-147 detected on wipe test ∴ passed
3. Temperature-vibration	Low level resonant frequency searc a sinusoidal sweep from 5 to 28 cps at 0.5" double amplitude (DA), 28 to 3000 cps at 20 g's; 3000 to 28 cps at 20 g's, and 28 to 5 cps at 0.5" DA at 1/2 octave/minute, and random vibration according to the following spectrum: 20 to 100 cps — 12 db/octave rise 100 to 1000 cps — 0.6 g^2/cps constant 1000 to 2000 cps — 12 db/octave roll-off Random vibration was applied for 30 minutes along each axis (90 minutes total). All vibration was applied along each of the three major axes, 50% (each) of the program conducted at +260°F and -260°F.	<0.001 μc Pm-147 detected on wipe test ∴ passed
4. Thermal vacuum	Exposed to a pressure of 10^{-5} mm Hg or lower for a minimum of 2 hrs at -300°F and then at +260°F	<0.001 μc Pm-147 detected on wipe test ∴ passed
5. Thermal shock	Stabilized parts at -321°F and then transferred to ovens at 600, 750 and 950°F. Wipe checked, held for 12 days and rewiped.	<0.001 μc Pm-147 detected on wipe test ∴ passed

B.2 SELF-LUMINOUS SWITCH TIPS

Test	Conditions	Results
1. Radiation level	0.2-0.5 mr/hr at 5 cm 1 mr/hr at 1 cm	Passed Passed
2. Flammability	Must withstand 350°F without bursting into flame 330°F - started to deform 380°F - definitely deformed 515°F - viscous puddle, but did not ignite	Passed
3. Brightness	Must have light brightness of 0.03 ft lambert or greater after 2 years	In progress
4. Corrosive Contaminant	Sprayed with 1% salt solution for 48 hours	Passed
5. Humidity	75-90°F at 95% relative humidity for 10 days	Passed
6. Temperature	-60°F for 24 hours +160°F for 24 hours	Passed Passed

		Conditions	Results
7.	Shock	Three 50 g shocks in each direction along three coordinate axes. Total 18 shocks.	Passed
8.	Oxygen atmosphere	4 days at 5 psig, 100% oxygen; at 50°F and 90°F at 50% relative humidity and dry for a total of 4 different tests. Each test lasting 24 hours.	Passed
9.	Thermal vacuum	0°F for 24 hours at 10^{-5} mm pressure; 160°F for 24 hours at 10^{-5} mm pressure	Passed
10.	Overstress tests		
	a. Thermal vacuum	Increase temperature at 10^{-5} mm pressure - partly deformed at 340°F	
	b. Temperature	1) At liquid nitrogen temp for 1 to 16 hrs	Passed
		2) At 500°F for 10 minutes	Passed
		3) At 900°F momentarily	Passed
	c. Shock	80 g along three coordinate axes	Passed

APPENDIX C

ENTRY HEATING ANALYSIS FOR CM DOCKING RING AND SM BAIL HANDLE

The basic problem is a determination of the disposition of self-luminous discs during atmospheric entry. The discs are mounted on the Apollo CM docking ring and in the SM bail handle. The first critical parameter associated with the discs is the melting temperature (400°F) of the epoxy bonding agent. The second critical parameter is the softening temperature of the fused silica disc (>2700°F). Since the critical parameters are temperatures, consideration must be given to a wide range of operational trajectories.

C.1 CM DOCKING RING

In lieu of a statistical study of operational entry trajectories, consideration has been given to key entry modes. As a general rule, temperature levels on a reentry vehicle are dependent on the integrated heat load. For lunar return the heat load range extends from the values for the high heat load (H_L), low heat rate trajectory to those for the high heat rate (H_R), low heat load trajectory. The AS-201 mission trajectory was selected as typical of orbital entry. Convective heating distributions around the Apollo CM are calculated and correlated in terms of a ratio to the instantaneous stagnation point heating for the vehicle. Experimental verification of heating rates on the flat face of the truncated Apollo CM has not been obtained. Theoretical estimates of the heating in this area of the docking ring yield values on the order of 5% of the reference (stagnation point) heating with secondary flow deviations to 10% of that same value. The lowest values of separated heating measured on the Apollo CM are 2.5% of the reference level. These low values were on the conical section, however, and are not applicable to the truncated region. The seemingly large disparity, between 5 and 10% of the reference heating, is due to the fact that these heating levels are on the order of 0.1% of the incident air relative energy flux.

The temperatures in the boundary region (where the epoxy bonds the discs to the ring) have been calculated for the three reference trajectories for both 5% and 10% of the reference heating rate. The results are shown in Figure 18. These calculations are based on a one-dimensional heating analysis and assume a surface emissivity of 0.9. The results show that the bond will exceed the first critical temperature of 400°F for all trajectories with the exception of the AS-201 trajectory with the 5% of reference heating rate.

The maximum temperature to be expected at the exterior surface of a disc is approximately 1400°F. This peak surface temperature occurs on the H_L trajectory at a location with a heating rate equal to 10% of the reference level. These results imply that in all operational cases a disc would not reach the second critical temperature of 2700°F if it remained in position on the CM.

The next question that arises is what happens to the discs when the epoxy temperature exceeds 400°F. There is a net acceleration of the CM in a direction normal to the vehicle axis of symmetry; however, this acceleration is very small compared to the deceleration along the axis. At an angle of attack of 30°, the normal acceleration is 8% of the axial deceleration. At a 20° angle-of-attack this figure is only 5.4%. Since the vehicle will trim somewhere between these angles, the coefficient of friction between the disc and the ring surface must be less than some minimum value that lies between 0.080 and 0.054 for the disc to leave the CM. There is no available information on the friction factor associated with the epoxy bond at elevated temperatures. As a frame of reference, the static friction coefficient of a waxed ski on dry snow is ~0.04. On this basis, it is anticipated that the discs will not leave the CM during hypersonic flight.

If, on the other hand, the discs do become detached, their disposition depends on their trim attitude. If the discs could maintain a trim attitude of flat face normal to the free stream their ballistic coefficient would be less than that of the CM. If this unlikely attitude were maintained the discs would survive entry.

A disc with a stable trim attitude of flat face parallel to the free stream would have a greater ballistic coefficient than the CM and would therefore lead the CM in flight. For this attitude (edge first) limiting boundaries have been calculated and are shown in Figure 19. The boundary of the no damage area is obtained by the point where the aerodynamic heating is less than the disc surface radiation at 2700°F. The boundary of complete disintegration is established by integrating back along a constant altitude trajectory to the point where the heat load is sufficient to completely melt the disc. Although the constant altitude trajectory is a poor approximation to an actual disc trajectory the resulting boundary is felt to be a reasonable approximation. The aero-

dynamic heating was calculated assuming a continuum flow over the disc and by the use of the Detra, Kemp and Riddell curve fit to the convective heating theory of Fay and Riddell.

Calculations were performed for the reference trajectories assuming the discs were released the instant the bond temperature reached 600°F. In every case the disc was completely melted in the order of a second. This assumed the flight path angle and the initial velocity of the disc on edge was equal to that of the CM at the time of disc release.

In terms of the CM docking ring self-luminous discs it is concluded that the discs will not leave the CM and will remain intact for the hypersonic portion of atmospheric entry. If the discs were released from the vehicle their disposition is defined by the boundaries shown in Figure 19.

C.2 SM BAIL HANDLE

The disposition of the self-luminous discs in the bail handle of the Apollo SM depends entirely on the behavior of the SM during entry. If the SM maintains an attitude with the bail handle in a forward position, the bail handle and the discs will undoubtedly disintegrate even during orbital entry. On the other hand, if the bail handle is shielded from the free stream flow, it is possible for the bail handle and the discs to splash down intact. The disposition of the discs in the SM cannot be considered separately from the behavior of the SM itself.

APPENDIX D

DISPERSION OF SELF-LUMINOUS SOURCES AND MICROSPHERES DURING REENTRY

D.1 INTRODUCTION

The Apollo spacecraft carries on board approximately 65 curies of Promethium 147 (Pm-147) as sealed self-luminous sources. The Pm-147 is tightly bound in 3M Brand radiating microspheres sealed in about 130 LM switch tips and 213 self-luminous discs contained in the CM docking ring, the LM docking target and the SM bail handle.

The dispersion of the self-luminous sources which reach the surface of the earth intact or the microspheres escaping from vaporized light sources during reentry is examined in this Appendix. From this analysis it is concluded that (1) should the self-luminous discs contained in the SM and LM survive reentry, they will probably be widely dispersed along with the other debris from these modules in a random pattern in an area approximately 3000 nautical miles in length in a down-range direction and 500 nautical miles in a cross range direction; 2) should a self-luminous disc or discs separate from the CM during reentry (which appears to be a remote possibility) it will survive and impact on the earth as an intact disc only if it maintains a trim attitude with the flat face normal to the free stream. In this unlikely event, the disc would impact to the rear of the CM footprint at a point determined by the trajectory parameters at time of release, the aerodynamic properties of the disc, and the action of the wind on the disc during its descent after reaching terminal velocity. In the event more than one disc separated, they would probably impact at widely separated points due to variations in trajectory parameters at time of release, aerodynamic properties, and winds acting on the discs during descent; 3) self-luminous sources (discs and switch tips) that experience reentry heating sufficient to cause their disintegration and release of the microspheres to the atmosphere will inject radioactive particles in the mesosphere or upper stratosphere. These microspheres may be further ablated by reentry heating and will be distributed throughout the atmosphere and deposited on the surface of the earth in a manner consistent with the "stirred reservoir model" of Holland and Klement.[1] In a worst case calculation in which the total 65 curies of Pm-147 was assumed to be injected into the upper stratosphere, it was determined that maximum tropospheric concentration was delivered in approximately 94 days, at which time a microsphere concentration of 1 microsphere per 70 cubic kilometers could be predicted. Maximum surface concentration occurs at approximately 908 days, when the concentration was calculated to be less than 1 microsphere per 40 square kilometers.

The following sections discuss reentry dispersion applicable to the SM, LM and CM self-luminous sources.

D.2 SM SELF-LUMINOUS SOURCE DISPERSION CHARACTERISTICS

The reentry heating analysis for the SM (see Section 4.2) indicates that the SM will disintegrate and expose all of the resulting pieces of debris to a severe thermal environment at an altitude of approximately 230,000 ft. The survivability analysis indicated that the aluminum and magnesium pieces would not survive the thermal environment. However, many of the steel and titanium pieces would survive to impact.

Since the SM self-luminous discs are recessed in the aluminum bail handle, it may be concluded that the bail handle melts and the discs are released to the atmosphere. The fused silica discs melt at only slightly lower temperatures than steel. It is therefore probable that some of the SM discs may survive to impact on the earth's surface with the other SM debris. It is probable that the discs that impact (a maximum of 24) will be randomly distributed throughout the dispersal envelope of the debris. This dispersal envelope is calculated to be approximately 3000 nautical miles in length in a down range direction and 500 nautical miles in width in a cross range direction.

SM discs that disintegrate due to extreme thermal environment will inject their microspheres in the mesosphere or upper stratosphere. The microspheres may in turn experience some ablation and form a diffuse line of radioactive particles in the upper atmosphere. It is probable that dispersion and removal of these particles from the atmosphere will occur in a manner which is analogous to the stirred reservoir model analyzed in Sect. D.5.

D.3 LM SELF-LUMINOUS SOURCE DISPERSION CHARACTERISTICS

The LM is not intended to return to the earth after a lunar mission. However, if reentry occurs after an aborted mission, a trajectory similar to the SM trajectory analyzed in Section 4.2 may describe the aerodynamic heating environment and structural loads it will experience. In this event, structural breakup and disintegration of aluminum and magnesium components can be anticipated. The self-luminous discs and switch tips will survive or disintegrate depending on thermal shielding provided by steel and titanium components in the debris.

The sources that survive (a maximum of 66 self-luminous discs and about 130 self-luminous switch tips) will probably be randomly distributed in the debris impact envelope of the LM. This envelope, by analogy to the SM analysis, may approximate an area of 3000 by 500 nautical miles.

The sources that disintegrate will inject a radioactive cloud into the mesosphere or stratosphere in a manner similar to the CM discussed in Section D.5.

D.4 CM SELF-LUMINOUS SOURCE DISPERSION CHARACTERISTICS

CM trajectory analyses for lunar and earth orbital reentry indicate that in almost all cases examined temperatures necessary for separation of the self-luminous discs from the docking ring are reached prior to the first peak in CM heating (the AS-201 trajectory calculation assuming 5% of stagnation heating rate was the one exception; see Figure 18). After this temperature is reached, separation may occur if the coefficient of friction between the disc and the fiberglass substructure is below a critical value determined by the CM angle of attack.

The discs that do not leave the CM during the high deceleration period will stay in place until the CM descends to an altitude of about 23,500 ft. At this time the forward heat shield is jettisoned and the forward heat shield with the discs attached will land near the CM.

The discs that separate will survive to land intact only if the disc enters the free stream in a trim attitude of the flat face normal to the free stream, which appears highly unlikely. In this situation the disc would rapidly fall behind the CM and follow a trajectory which is determined by its physical characteristics and the trajectory parameters at the time of separation. Since it is not likely that more than one disc will separate at a given moment and it is probable that each disc will differ in physical characteristics from the others due to adhering epoxy, the trajectories each disc follows until the time terminal velocity is reached may result in significant dispersion of the discs that separate from the CM. After terminal velocity is reached the discs will fall at terminal velocity as given by Newton's law for turbulent motion and achieve further dispersion due to the action of the winds during descent. A calculation of a representative displacement due to winds during terminal velocity descent (assuming terminal velocity is reached at 50,000 meters altitude) is presented in Section D.6.

It has been calculated that the discs that separate from the CM and assume a trim attitude other than flat face normal to the free stream will disintegrate within one second (see Figure 19). In this event the microspheres will be released to the mesosphere or stratosphere and may experience further ablation. The resulting diffuse cloud of radioactive particles will be dispersed in the atmosphere and removed from the atmosphere in a manner similar to the stirred reservoir model previously discussed. Section D.5 analyzes the dispersion and deposition of microspheres using the stirred reservoir model.

D.5 DISPERSION OF MICROSPHERES

Trajectory analyses of lunar return and earth orbital return reentry modes of the Apollo Command Module (CM) indicate that in all cases in which separation of the self-luminous discs from the CM occur, the altitude and velocity at separation are sufficient to cause disc burnup within one second after separation although some could survive due to trim attitude. Partial burn-up of the microspheres is also probable, producing a cloud of radioactive vapor. Since the microspheres are approximately 20 microns in size, the particle-size distribution within the cloud can be expected to range from about 20 microns to appreciably smaller sizes. Regardless of the dynamic heat loads experienced by the microspheres, the net result is that the atmosphere is injected with a distribution of radioactive particles 20 microns or less in diameter in the region at which separation occurs. In the earth orbital case the deposition occurs at about 145,000 ft (in the stratosphere). In the lunar return modes of reentry, the deposition can occur in the region from 154,000 ft (stratosphere) to 233,000 ft (mesosphere).

For the probable particle size distributions in question and at the altitudes of deposition, the "stirred reservoir" model based on bomb test fallout data appears acceptably valid.[1] The atmosphere is taken as a series of three reservoirs (mesosphere, stratosphere, and troposphere) separated by permeable barriers, so there is a "mean residence time" in each reservoir. Dobry[2] indicates mean residence times of 5 years in the mesosphere (>160,000 ft), 2 years in the stratosphere (160,000 ft to 40,000 ft), and 21 days in the troposphere (<40,000 ft), and accounts for the well known non-uniformity of fallout by assuming that 2/3 of the activity falls onto 1/6 of the earth's surface (between 30 and 60 degrees north).

D.5.1 Radioactive Fallout Analysis

The radioactive material is introduced into the atmosphere at altitudes ranging from 145,000 ft to 233,000 ft. The principal mechanisms by which removal of radioactivity from the atmosphere occurs are: gravitational settling, scavenging of radioactive particles by falling precipitation, radioactive decay, and deposition by diffusion.

The basic removal relationship is

$$\frac{dA(t)}{dt} = -kA(t)$$

where

$\frac{dA(t)}{dt}$ = activity depletion rate

$A(t)$ = regional activity burden at time, t

k = proportionality constant = removal rate

$1/k$ = mean residence time

$0.693/k$ = half residence time

The solution of this equation is:

$$A(t) = A(0) \exp(-kt)$$

where $A(0)$ is the initial Pm-147 activity at $t = 0$.

For the case of reentry burnup debris, the mean residence times of Dobry are used, namely:

1) Mesosphere (above 160,000 ft) - 5 years
2) Stratosphere (40,000-160,000 ft) - 2 years
3) Troposphere (below 40,000 ft) - 21 days

A worst case evaluation follows by considering that the total Pm-147 activity available is 65 c and total injection occurs in the stratosphere rather than in the mesosphere. For this case the activity equations for the stratosphere, troposphere and earth's surface are as follows:

Stratosphere

rate of change of activity in stratosphere = minus rate of loss of activity to the troposphere minus rate of loss of activity due to radioactive decay

$$\frac{dA_1(t)}{dt} = -k_1 A_1(t) - \lambda A_1(t) \qquad (D\text{-}1)$$

Troposphere

rate of change of activity in troposphere = plus rate of gain of activity from stratosphere minus rate of loss of activity to the earth's surface minus rate of loss of activity due to radioactive decay

$$\frac{dA_2(t)}{dt} = k_1 A_1(t) - k_2 A_2(t) - \lambda A_2(t) \qquad (D\text{-}2)$$

Earth's surface

rate of change of activity deposited on earth's surface = plus rate of gain of activity from troposphere minus rate of loss of activity due to radioactive decay

$$\frac{dA_3(t)}{dt} = k_2 A_2(t) - \lambda A_3(t) \qquad (D\text{-}3)$$

The solutions to these activity equations are:

Stratosphere - Eq. (D-1):

$$A_1(t) = A(0) \exp\left[-(k_1 + \lambda)t\right] \qquad (D-4)$$

Troposphere - substituting $A_1(t)$ from Eq. (D-4) into (D-2) gives:

$$\frac{dA_2(t)}{dt} = k_1 A(0) \exp\left[-(k_1 + \lambda)t\right] - (k_2 + \lambda) A_2(t)$$

The solution of this equation is:

$$A_2(t) = \frac{k_1 A(0)}{k_2 - k_1} \left\{\exp\left[-(k_1 + \lambda)t\right] - \exp\left[-(k_2 + \lambda)t\right]\right\} \qquad (D-5)$$

Earth's surface - substituting $A_2(t)$ from Eq. (D-5) into (D-3) gives:

$$\frac{dA_3(t)}{dt} = \frac{k_1 k_2 A(0)}{k_2 - k_1} \left\{\exp\left[-(k_1 + \lambda)t\right] - \exp\left[-(k_2 + \lambda)t\right]\right\} - \lambda A_3(t)$$

Setting $\left[k_1 k_2 A(0)/(k_2 - k_1)\right] = C_1$ leads to the solution

$$A_3(t) = -\frac{C_1}{k_1} \exp\left[-(k_1 + \lambda)t\right] + \frac{C_1}{k_2} \exp\left[-(k_2 + \lambda)t\right] + I_1 \exp(-\lambda t) \qquad (D-6)$$

where I_1 is a constant of integration. When $t = 0$,

$$I_1 = \frac{C_1}{k_1} - \frac{C_1}{k_2}$$

Setting $-\frac{C_1}{k_1} = B_1$, $-\frac{C_1}{k_2} = B_2$, and $I_1 = B_3$ gives

$$A_3(t) = B_1 \exp\left[-(k_1 + \lambda)t\right] - B_2 \exp\left[-(k_2 + \lambda)t\right] + B_3 \exp(-\lambda t) \qquad (D-7)$$

Evaluation of Constants

k_1 = rate of loss of activity to troposphere (stratosphere mean residence time of 2 years)
$= 0.693/730 = 0.95 \times 10^{-3}$ day^{-1}

k_2 = rate of loss of activity to the earth's surface (troposphere mean residence time of 21 days)
$= 0.693/21 = 3.3 \times 10^{-2}$ day^{-1}

λ = decay constant of Pm-147 (half life of 2.6 years)
$= 7.36 \times 10^{-4}$ day^{-1}

$k_1 + \lambda = 0.00168$ day^{-1}

$k_2 + \lambda = 0.0337$ day^{-1}

$A(0)$ = 65 curies of Pm-147

$$C_1 = \frac{k_1 k_2 A(0)}{k_2 - k_1} = 0.0635 \text{ curies}$$

$$B_1 = \frac{-C_1}{k_1} = -66.925 \text{ curies}$$

$$B_2 = \frac{-C_1}{k_2} = -1.925 \text{ curies}$$

$$B_3 = B_2 - B_1 = 66.925 - 1.925 = 65 \text{ curies}$$

Maximum Burden (A(0) = 65 curies)

a. Troposphere

To estimate time for maximum burden in the troposphere, set the first derivative of Eq. (D-5) equal to 0 and solve for t.

$$A_2(t) = \frac{k_1 A(0)}{k_2 - k_1} \left\{ \exp\left[-(k_1 + \lambda)t\right] - \exp\left[-(k_2 + \lambda)t\right] \right\} \qquad (D\text{-}5)$$

Taking the first derivative and setting it equal to 0:

$$\frac{d\left[A_2(t)\right]}{dt} = k_1 A(0) e^{-(k_1 + \lambda)t} - (k_2 + \lambda) A_2(t) = 0 \qquad (D\text{-}8)$$

where $A_2(t) = \frac{k_1 A(0)}{k_2 - k_1} \left(e^{-(k_1 + \lambda)t} - e^{-(k_2 + \lambda)t} \right)$

Solving for $A_2(t)$:

$$A_2(t) = 1.925 \left(e^{-(0.00168)t} - e^{-(0.03373)t} \right)$$

Substituting this value of $A_2(t)$ in Eq. (D-8) gives

$$\frac{d\left[A_2(t)\right]}{dt} = 0.0617 \left(e^{-(0.00168)t} \right) - 0.06493 \left(e^{-(0.00168)t} - e^{-(0.03373)t} \right) = 0 \qquad (D\text{-}9)$$

The time of maximum burden is then numerically estimated for the time when t changes sign:

t = 1 ,	$\frac{d\left[A_2(t)\right]}{dt}$	= +0.059
t = 93 ,	"	= +0.0000563
t = 94 ,	"	= -0.000033
t = 95 ,	"	= -0.0001
t = 100 ,	"	= -0.0005

Using t = 94 in Eq. (D-8), $A_2(t) = 1.563$ curies

The maximum atmospheric burden in the troposphere therefore occurs at about 94 days after reentry, at which time 1.563 curies of Pm-147 will be distributed throughout the troposphere.

b. Earth's Surface (A(0) = 65 curies)

To estimate the maximum burden on the earth's surface, set the first derivative of Eq. (D-6) equal to zero and solve for t.

$$A_3(t) = \frac{-C_1}{k_1} \exp -(k_1 + \lambda)t + \frac{C_1}{k_2} \exp -(k_2 + \lambda)t + I \exp -\lambda t \qquad (D\text{-}6)$$

$$\frac{d\left[A_3(0)\right]}{dt} = C_1 \left(\exp -(k_1 + \lambda)t - \exp -(k_2 + \lambda)t \right) - \lambda A_3(t) = 0 \qquad (D\text{-}10)$$

where $A_3(t) = \frac{-C_1}{k_1} \exp -(k_1 + \lambda)t + \frac{C_1}{k_2} \exp -(k_2 + \lambda)t + I \exp -\lambda t$

with $C_1 = \frac{k_1 k_2 A(0)}{(k_2 - k_1)} = 0.0635$

$$A_3(t) = -66.925 \exp -(0.00168)t + 1.925 \exp -(0.03373)t + 65 \exp -(0.00073)t$$

Substituting in $A_3(t)$ in Eq. (D-10) gives

$$\frac{dA_3(t)}{dt} = 0.0635 \left[\exp -(0.00168)t - \exp -(0.03373)t\right]$$

$$-0.00073 \left[66.925 \exp -(0.00168)t + 1.925 \exp -(0.03373)t + 65 \exp -(0.00073)t\right] = 0$$

The time of maximum burden is then numerically estimated for the time when t changes sign:

t = 700	$\frac{dA_3(t)}{dt}$	= +0.00621
t = 900	"	= +0.00018
t = 907	"	= +0.000019
t = 908	"	= -0.000043
t = 910	"	= -0.0000506
t = 915	"	= -0.0001

Thus, the time for maximum burden on the earth's surface is 908 days. Substituting this value in Eq. (D-6) gives the maximum Pm-147 burden of approximately 18.9 curies. Therefore the maximum activity may be expected at about 900 days, at which time the distributed Pm-147 activity will be about 19 curies.

D.5.2 Troposphere and Surface Concentrations

The concentration of radioactivity in the troposphere may be found by dividing the tropospheric burden by tropospheric volume. Recent evaluations of bomb fallout patterns showed that two-thirds of the tropospheric burden lies between 30 and 60 degrees latitude in the hemisphere where the material is released.[3] The volume of this region, for a height of 10.7 kilometers, is 7.83×10^{17} m^3. The maximum tropospheric concentration is then estimated to be 1.35×10^{-18} μc/cc. The maximum permissible exposure (MPC) for the general public is 2×10^{-9} μc/cc. Therefore the maximum concentration of Pm-147 in the troposphere is about 9 orders of magnitude less than the MPC.[4]

If it is assumed that the microspheres survive intact, then the maximum concentration of microspheres can be estimated by dividing the tropospheric activity concentration by the microsphere activity at the time in question, namely t = 94 days. Assuming the microspheres have an initial activity of 0.1 μc when introduced into the biosphere, then at t = 94 day (maximum tropospheric Pm-147 concentration), the activity in the microspheres will have decayed to 9.3×10^{-2} μc/microsphere. This will result in a "microsphere concentration" of 1.45×10^{-16} microsphere per cc or one microsphere may be expected in 70 cubic kilometers of atmosphere (one microsphere above 2.64 x 2.64 km square area).

The surface concentration may be computed by dividing the maximum surface burden by surface area. Again, two-thirds of the activity will lie in a 30 to 60 degree latitude band about one hemisphere. The area of the earth's surface in the band described is approximately 9.34×10^{13} m^2. Maximum surface concentration over this area would be 1.35×10^{-13} μc/cm^3.

Again assuming that the microspheres survive intact, then the maximum activity concentration of microspheres on the surface of the earth can be estimated by dividing the earth's surface concentration by the microsphere activity at t = 908 days. At 908 days, the microsphere concentration would be 2.65×10^{-10} microspheres/cm^2 or one microsphere every 40 square kilometers.

It should be noted, however, that since natural processes such as leaching of the soil and the biological uptake by animals will occur continuously during the deposition process, the maximum surface concentrations actually available to interact with man will be considerably less than that indicated by the above calculations.

In summary, the Pm-147 contained in the self-luminous sources is assumed to be introduced into the biosphere at altitudes ranging from 140,000 to 233,000 ft. A "worst case" computation is made assuming the self-luminous discs follow the profile of the CM. The "stirred reservoir" model of Holland[2] is used to

estimate the concentration of Pm-147 activity from its release in the stratosphere, mixing into the troposphere, and finally depositing on the earth's surface. (If release in the mesosphere were assumed, then another mixing layer would be introduced and the resultant activity concentrations would be very much lower than for case analyzed.) The maximum tropospheric aerosol concentration would occur at t = 94 days producing a "virtual concentration" of 1.35×10^{-18} μc/cc with a "microsphere concentration" of one microsphere per 70 km^3 of atmosphere (one microsphere above every 2.64 x 2.64 km square area). The maximum activity concentration on the earth's surface would occur at t = 908 days producing a "virtual concentration" of 1.35×10^{-13} $\mu c/cm^3$ with a "microsphere concentration" of one microsphere per 40 km^2.

D.6 DISC DISPERSION DURING TERMINAL VELOCITY DESCENT

In the following calculations, particles are assumed to proceed earthward with essentially terminal velocity while being transported horizontally by wind. The terminal velocity for large particles is given by Newton's law for turbulent motion:

$$V = \left(\frac{4\,\rho_g P}{3\,\rho_a C_D}\right) \times 10^{-7} \text{ (km/sec)}$$

where the particle or disc diameter, P = 16,000, is in microns; gravitational acceleration is g = 980 cm/sec^2; the particle density is ρ = 2.21 (gm/cm^3); air density is $\rho_a = 1.3 \times 10^{-3} \exp -Z/7$ (gm/cm^3) at altitude Z_1 (km); and dimensionless drag coefficient for turbulent motion is C_D = 0.44.

In falling from Z_1 to Z_2 (Z_1 representing upper wind layer boundary; Z_2 lower wind layer boundary), the wind will carry a particle a distance $\Delta X = \int_{Z_1}^{Z_2} \frac{V_W}{V}\, dZ = \frac{V_W}{V} Z \Big]_{Z_1}^{Z_2}$, where V is the terminal velocity from above and V_W is the wind speed at altitude Z. The following wind speed profile equations were taken from Reference 5:

$$\left[V_W\right]_{29}^{50} = (1.32\,Z_1 - 32.3) \text{ (m/sec)} \quad \ldots\ 29.0 \le Z_1 \le 50 \text{ (km)},$$

$$\left[V_W\right]_{20}^{29} = 6 \text{ (m/sec)} \quad \ldots\ 20.0 \le Z_1 \le 29 \text{ (km)},$$

$$\left[V_W\right]_{10.5}^{20} = (46 - 2\,Z_1) \text{ (m/sec)} \quad \ldots\ 10.5 \le Z_1 \le 20 \text{ (km)},$$

$$\left[V_W\right]_{1.5}^{10.5} = (2.85 + 2.1\,Z_1) \text{ (m/sec)} \quad \ldots\ 1.5 \le Z_1 \le 10.5 \text{ (km)},$$

$$\left[V_W\right]_{0}^{1.5} = 6 \text{ (m/sec)} \quad \ldots\ 0 \le Z_1 \le 1.5 \text{ (km)}.$$

For example, if Z_1 = 50 km, then V_W = 0.066 km/sec and V = 1.01 km/sec. In falling from 50 km to 29 km then, the particle will travel a horizontal distance of 1.37 km, as $\Delta X = \int_{50}^{29} \frac{0.066}{1.01}\, dz = \left[0.065\, z\right]_{50}^{29} = -1.37$ km.

Note that since the wind speed is decreasing with altitude between 50 km and 29 km, using the greater Z value presents a conservative estimate, that is the greatest horizontal displacement is given. The wind speed values are all negative as this distance is in the downwind direction.

The distance that a particle of size 16,000 microns traverses in each altitude layer is given in Table D-1, and the total distance, given a release altitude, is obtained by summing the ΔX's of the altitude layers the particle falls through in Table D-1, and are given in Table D-2.

TABLE D-1 TRAVERSE DISTANCE FOR SPECIFIC ALTITUDE LAYER

Altitude Interval		V	V_W	ΔX
Z_1(km)	Z_2(km)	(km/sec)	(km/sec)	(km)
50	29	1.01	0.066	1.37
29	20	0.229	0.006	0.239
20	10.5	0.119	0.006	0.479
10.5	1.5	0.06	0.0249	3.73
1.5	0	0.03	0.006	0.3

TABLE D-2 TOTAL TRAVERSE DISTANCE FOR SPECIFIC INITIAL ALTITUDE

Initial Altitude (Z_1) (km)	$\sum \Delta X$ (km)
50	6.118
29	4.748
20	4.509
10.5	4.03
1.5	0.3

In the selected wind profile, the wind speed is always constant or decreasing in each altitude layer except one, between 20 km and 10.5 km. In calculating V_W at the maximum altitude of each layer, Z_1, the maximum wind speed was obtained, with the exception of the 1.5 to 10.3 km altitude layer. But, since there are two such altitude layers where the wind is decreasing, the total value of X is still conservative, i.e., worst case.

References

1. Holland, J. Z., and Klement, A. W., Jr., Fallout Prediction Techniques, SC-DC-3553 (January 1964).
2. Dobry, T. J., SNAP 9A Radioisotope Fueled Generator, Final Safety Analysis for the Transit Mission, MND-P-2775-2, March 1963 (Secret-RD).
3. Stebbins, A. K., HASP Second Special Report on High Altitude Sampling Program, DASA-539B, August 1961.
4. U.S. Department of Commerce Handbook 69, Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure.
5. Handbook of Geophysics, Revised Edition, MacMillan Co., New York, 1961.

APPENDIX E

RADIATION EXPOSURE FROM Pm-147

E.1 Pm-147 PROPERTIES

Promethium 147, with a 2.6 year half-life, decays to Samarium 147 by beta particle emission. The 0.22 Mev beta has a 0.12 Mev gamma associated with it.

The critical organ for soluble Pm-147 is the bone, i.e., it is a bone seeker similar to calcium; the lungs and liver are also affected but to a lesser extent. The intestinal tract is the critical organ for insoluble Pm-147, with the lower large intestine the most critical organ.

The Pm-147 as contained in the 3M Brand Radiating Microspheres is not in a soluble form and cannot enter the bloodstream. If a Pm-147 microsphere is ingested it will pass through the intestinal tract with the feces.

The most sophisticated analysis cannot guarantee that what is proposed will occur. For this reason each system, as well as a single disc, a switch tip, and a single microsphere will be discussed for intact reentry.

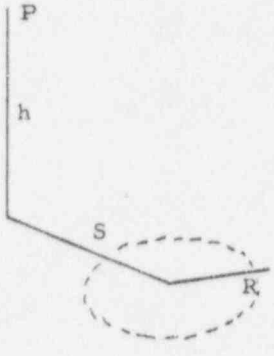
E.2 INTACT SYSTEMS

The assumption is made that each system is protected during the reentry heating phase and is recovered intact.

E.2.1 Docking Ring

The docking ring has 123 self-luminous discs (3M Model 1E2J), each containing 300 mc of Pm-147. The measured dose rate from the front surface of a single disc is about 0.4 mr/hr at 1 foot. The discs are attached to a ring of 21.25 in. radius on one-inch centers. The dose rate at any point along a line through the center of the ring and perpendicular to the plane of the ring is given by

$$D_p = \frac{D_o (2\pi R\, k)}{\left[(h^2 + S^2 + R^2)^2 - 4R^2S^2\right]^{1/2}} \qquad (E\text{-}1)$$



in which

D_o = dose rate at 1 foot from single disc = 0.4 mr/hr
$(2\pi R\, k)$ = total number of discs in ring = 123
R = radius of ring (ft) = 1.77 ft
S = distance from P to the axis of ring (ft)
h = vertical distance from P to the plane of the ring (ft)

For points on the axis of the ring S = 0 and equation (E-1) reduces to

$$D_p(S=0) = \frac{49.2}{h^2 + 3.14} \text{ mr/hr} \qquad (E\text{-}2)$$

Table E-1, column 2, lists the dose rate as a function of distance along the axis from the plane of the ring.

TABLE E-1 DOSE RATE VS. DISTANCE

Distance (ft)	Dose Rate	
	Ring Axis (mr/hr)	Ring Plane (mr/hr)
0.25	16	13
0.5	15	6
1	12	3
2	7	1
3	4	0.6
4	3	0.4
5	2	0.3
10	0.5	0.1

A second orientation to be considered is from a point in the plane of the ring. For this case h=0 and equation (E-1) reduces to

$$D_p(h = 0) = \frac{12.3}{\left[S^2 - 3.14\right]} \text{ mr/hr} \qquad \text{(E-3)}$$

Note: D_o in this case is 0.1 mr/hr at 1 ft from the disc edge.

The dose rates as a function of distance from the edge of the ring are tabulated in Table E-1, Column 3.

In these calculations the activity was assumed to be evenly distributed around the circumference of the ring which will result in errors for dose rates at short distances where the actual geometry is of importance. These effects are small at distances of about ten times the center-to-center spacing of the discs (i.e., beyond about 1 foot). A similar error exists as a result of the grouping of discs into three regions separated by 9° intervals. These errors will likewise be negligible at distances over 1 foot.

E.2.2 Bail Handle

The 24 discs in the bail handle are arranged in two rows of 12 discs each. For dose rate calculation purposes the bail handle is considered as a line source one foot long. The equation for calculating the dose rate at a point P from a line source L units long is given by:

$$D_p = \frac{D_o(KL)}{Lh}\left[\tan^{-1}\left(\frac{2S+L}{2h}\right) - \tan^{-1}\left(\frac{2S-L}{2h}\right)\right] \qquad \text{(E-4)}$$

in which (KL) is the number of discs distributed along the line (24), D_o is the gamma dose rate per disc at 1 foot (0.4 mr/hr), and L, S, h are defined in Figure E-1. In the case of the dose rate as a function of distance from the line source at its midpoint, S=0, and equation (E-4) reduces to:

$$D_p(S=0) = \frac{2D_o(KL)}{Lh}\tan^{-1}\left(\frac{L}{2h}\right) \qquad \text{(E-5)}$$

$$D_p(S=0) = \frac{19}{h}\tan^{-1}\left(\frac{1}{2h}\right) \qquad \text{(E-6)}$$

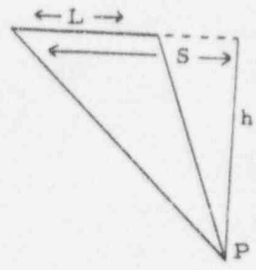


Figure E-1

Using equation (E-6) the dose rate to a point P on a line passing through the midpoint of the handle was calculated for various distances h greater than one foot. These are tabulated in Table E-2, Column 2.

The dose rate along the axis of the bail handle can be calculated by:

$$D_p = \frac{D_o N}{S^2 - 0.25L^2} \qquad \text{(E-7)}$$

Substituting N = 24; D_o = 0.05 mr/hr; L = 1 ft

$$D_p = \frac{1.2}{S^2 - 0.25} \qquad \text{(E-8)}$$

The values from this equation are given in Table E-2, Column 3.

TABLE E-2 DOSE RATE VS. DISTANCE FROM BAIL HANDLE

Distance* (ft)	Perpendicular Dose Rate (mr/hr)	Axis Dose Rate (mr/hr)
0.25	75**	10**
0.5	27**	3**
1	9	0.6
2	2	0.2
3	1	0.1
4	0.6	0.06
5	0.4	0.04
10	0.1	0.01

* Measured from center of bail handle for Column 2; measured from end of bail handle for Column 3.

**Note: Equation (E-8) was not used in calculating the dose rate at the first two distances (0.25 and 0.5 ft) because the distributed configuration of the discs does not approximate a continuous line source at small distances. The geometry was drawn to scale and the separation distance to each source was measured. The dose rate at each distance was calculated and the individual dose rates were summed to give the total dose rate. At one foot the two methods gave similar results, and the value given by equation (E-6) was used in Table E-2.

E.2.3 Docking Target

The docking target consists of a 13 in. diameter ring with a "T"-shaped marker on a pedestal spaced 14 in. in front of the ring.

The ring has 40 self-luminous discs spaced evenly on 1 in. centers. There are three radial protrusions with two discs on 1 in. centers each at 90° intervals.

The "T" marker has three 5 in. long arms containing 5 discs each on 1 in. centers, with 5 more discs clustered at the junction of the arms. The arms and the radial protrusions on the ring are in alignment when viewed along the ring axis.

The total number of self-luminous discs is 66.

For simplicity the calculation of dose rate is broken down into the linear superposition of individual ring and line sources, using the formulas developed for the docking ring and bail handle in previous sections.

The ring with the protrusions constitutes a simple ring source. The three arms of the "T" comprise three separate line sources. Finally, the center of the "T" is treated separately as a point source.

Ring. The equation for the dose rate due to the ring alone is:

$$D_p(\text{ring}) = \frac{D_o N}{\sqrt{(S^2 + h^2 + R^2)^2 - (2RS)^2}} \qquad (E\text{-}9)$$

where

D_o = dose rate at 1 foot from a single disc = 0.4 mr/hr
N = number of discs in ring = 46
P = point at which dose rate is desired
h = distance of point P above the plane of the ring
S = distance of point P from the central axis of the ring
R = radius of the ring = 6.5 in. = 0.54 feet.

The dose rate on the axis then reduces to:

$$D_p(\text{ring axis}) = \frac{18.4}{h^2 + 0.30} \qquad (E\text{-}10)$$

"T" Center. The cluster of 5 discs at the center of the "T" is treated as a point source with the radiation calculated for locations at distances of 1 foot and more. All distances are measured from the center of the "T" marker.

$$D_p(\text{"T" center}) = \frac{D_o N}{S^2 + h^2} \qquad (E\text{-}11)$$

where N = 5 discs.

On the ring axis this reduces to:

$$D_p(\text{"T" center}) = \frac{2}{h^2} \quad (\text{for } h > 1 \text{ ft}) \qquad (E\text{-}12)$$

"T" Arms. These line sources have their maximum effect if point P is oriented along the pedestal of the "T" (also the ring axis).

The equation is:

$$D_p(\text{"T" arms}) = \frac{3 D_o N}{L h} \left[\tan^{-1} \left(\frac{2R_T + L}{2h} \right) - \tan^{-1} \left(\frac{2R_T - L}{2h} \right) \right] \qquad (E\text{-}13)$$

where

N = 5 discs

L = length of arm = 5 in. = 0.42 feet

R_T = axis to midpoint of arm = $\frac{L}{2}$ = 0.21 feet

This equation reduces to:

$$D_p(\text{"T" arms}) = \frac{14}{h} \tan^{-1} \left(\frac{0.42}{h} \right) \qquad (E\text{-}14)$$

Summation. The contributory dose rates obtained with equations (E-10, (E-12) and (E-14) and the total dose rates at various distances from the center of the "T" are given in Table E-3.

TABLE E-3 DOSE RATE FOR EACH CONTRIBUTION AND TOTAL

Distance (ft)	Ring (mr/hr)	"T" (mr/hr)	Total (mr/hr)
0.25	46	72	80
0.50	32	23	29
1	14	9	12
2	4.3	2.3	4.2
3	2.0	1.0	2.1
4	1.1	0.59	1.3
5	0.7	0.38	0.86
10	0.2	0.09	0.24

E.3 POTENTIAL RADIATION EXPOSURE FROM A SINGLE MICROSPHERE

Appendix D provides a reentry analysis. The probability that an individual would come in contact with more than one microsphere is very small.

There are two modes of exposure to a microsphere, external and internal. Each of these are discussed in the following sections.

E.3.1 External Exposure

A microsphere that makes contact with and adheres to the skin will impart a surface dose. The maximum range of a 0.22 Mev beta particle is about 50 mg/cm^2. This corresponds to about 500 microns of tissue.

The microsphere is small in comparison with the range of the Pm-147 beta particle. The small amount of absorbtion by the microsphere is ignored in this analysis to enable determination of the maximum potential exposure dose rate.

The top, dead, layer of skin is considered to be ~70 microns thick. Since no harm can come from energy absorbed by dead tissue, the effect on tissue beyond a depth of 70 microns determines the hazard. This axiom is based on recommendations of the National Committee on Radiation Protection as contained in NBS Handbook 59, "Permissible Dose from External Sources of Ionizing Radiation", 1954, page 39. Specifically, it is stated that the cells in the basal layer of the epidermis require the greatest protection, and they lie primarily

at a depth of 7 mg/cm^2 (70 microns). In some cases (palms of manual workers) this depth is much greater.

The method for determining the dose rate in tissue associated with a beta point source (microsphere) was taken from Radiation Dosimetry, G. Hine and G. Brownell, Academic Press, 1956, page 704.

The dose rate in rads per beta disintegration at a distance of X cm is given by Hine and Brownell on page 709 as:

$$J(X) = \frac{k}{(\nu X)^2} \left\{ c \left[1 - \left(\frac{\nu X}{c} \right) \exp 1 - \left(\frac{\nu X}{c} \right) \right] + \nu X \exp 1 - \nu X \right\} \qquad \text{(E-15)}$$

with $\left[1 - \left(\frac{\nu X}{c} \right) \exp 1 - \left(\frac{\nu X}{c} \right) \right] = 0$ for $x \geq \frac{c}{\nu}$

where $J(X)$ = dose rate in rads/dis at distance X cm

ν = absorption coefficient in cm^{-1}

c = dimensionless parameter

k = normalizing constant

Integration over all space gives the equation for k as:

$$k = 1.28 \times 10^{-9} \rho^2 \nu^3 \bar{E}_\beta a$$

where ρ = density of medium = 1.0 g/cc for tissue

$\bar{E}_\beta$ = average energy of beta-particle spectrum

$a = \left[3c^2 - (c^2 - 1)\, e \right]^{-1}$

For tissue, Hine and Brownell give (page 712):

$$\nu = \frac{18.6}{\left[E_o - 0.036 \right]^{1.37}} \left(2 - \frac{\bar{E}_\beta}{\bar{E}^*_\beta} \right) \quad \text{cm}^2/\text{g of tissue}$$

$c = 2$ for $0.17 < E_o < 0.5$ Mev

where E_o = maximum beta-particle energy

$\bar{E}^*_\beta$ = hypothetical average beta-particle energy for allowed beta spectrum.

Since Pm-147 has an allowed shape, the shape factor ratio of $(\bar{E}_\beta / \bar{E}^*_\beta)$ can be taken as unity.* The maximum energy of the spectrum is 0.23 Mev, and the average energy was determined (from the graph on page 698 of Hine and Brownell) to be 0.06 Mev.

A computer program was set up to calculate the dose rate at 5 micron increments of distance out to 500 microns. The results are presented in Table E-4. The integrated spatial dose is the normalizing factor k.

The amount of activity in a single microsphere has a nominal value of 0.1 μc or 1.34×10^7 beta disintegrations per hour. With this quantity, the tissue dose rate at 70 microns is 1160 rads/hour.

This value is the dose rate at a point directly under the microsphere and at a depth of 70 microns. As pointed out in NBS Handbook 59, op-cited, page 28, the proper value is that taken over an area of skin which may be of the order of one square centimeter.

The averaged value of J(X) over an area of radius R at a depth D was determined analytically from Equation (E-15) as:

$$\bar{J}(D,R) \quad \frac{2R}{(\nu R)^2} \left[c \ln \frac{\sqrt{D^2 + Rc^2}}{D} + \exp 1 - \nu D - \exp 1 - \nu \sqrt{D^2 + R^2} - c \exp 1 - \left(\frac{\nu D}{c} \right) + c \exp 1 - \left(\frac{\nu}{c} \sqrt{D^2 + Rc^2} \right) \right] \qquad \text{(E-16)}$$

where $Rc = \sqrt{\left(\frac{c}{\nu} \right)^2 - D^2}$

* Experimental Nuclear Physics, Vol. III, E. Segre, editor, John Wiley and Sons, 1959, page 533.

TABLE E-4

BETA POINT SOURCE DOSE DISTRIBUTION FOR PM147 IN SOFT TISSUE

MAXIMUM BETA ENERGY IS 0.225 MEV AVERAGE IS 0.062 MEV
PARAMETER C IS 2.00 SHAPE FACTOR IS 1.00
TISSUE DENSITY IS 1.00 GRAMS PER CC
CALCULATED ABSORPTION COEFF IS 0.1822E 03 SQ CM PER GRAM
INTEGRATED SPATIAL DOSE IS 0.1665E 05 RADS PER HR PER MICROCURIE

TABLE OF DOSE IN RADS PER HOUR PER MICROCURIE AT INDICATED DISTANCE IN MICRONS

DIST	DOSE	DIST	DOSE	DIST	DOSE	DIST	DOSE	DIST	DOSE
5.	0.398E 07	10.	0.982E 06	15.	0.427E 06	20.	0.233E 06	25.	0.144E 06
30.	0.962E 05	35.	0.677E 05	40.	0.494E 05	45.	0.371E 05	50.	0.285E 05
55.	0.223E 05	60.	0.177E 05	65.	0.142E 05	70.	0.116E 05	75.	0.954E 04
80.	0.791E 04	85.	0.661E 04	90.	0.557E 04	95.	0.473E 04	100.	0.405E 04
105.	0.349E 04	110.	0.303E 04	115.	0.265E 04	120.	0.232E 04	125.	0.203E 04
130.	0.178E 04	135.	0.157E 04	140.	0.138E 04	145.	0.121E 04	150.	0.107E 04
155.	0.949E 03	160.	0.839E 03	165.	0.743E 03	170.	0.658E 03	175.	0.584E 03
180.	0.518E 03	185.	0.460E 03	190.	0.409E 03	195.	0.364E 03	200.	0.324E 03
205.	0.288E 03	210.	0.257E 03	215.	0.229E 03	220.	0.204E 03	225.	0.182E 03
230.	0.163E 03	235.	0.145E 03	240.	0.130E 03	245.	0.116E 03	250.	0.104E 03
255.	0.932E 02	260.	0.835E 02	265.	0.747E 02	270.	0.670E 02	275.	0.600E 02
280.	0.538E 02	285.	0.482E 02	290.	0.433E 02	295.	0.388E 02	300.	0.349E 02
305.	0.313E 02	310.	0.281E 02	315.	0.252E 02	320.	0.227E 02	325.	0.204E 02
330.	0.183E 02	335.	0.165E 02	340.	0.148E 02	345.	0.133E 02	350.	0.120E 02
355.	0.108E 02	360.	0.974E 01	365.	0.877E 01	370.	0.790E 01	375.	0.711E 01
380.	0.641E 01	385.	0.577E 01	390.	0.520E 01	395.	0.469E 01	400.	0.422E 01
405.	0.381E 01	410.	0.343E 01	415.	0.310E 01	420.	0.279E 01	425.	0.252E 01
430.	0.227E 01	435.	0.205E 01	440.	0.185E 01	445.	0.167E 01	450.	0.151E 01
455.	0.136E 01	460.	0.123E 01	465.	0.111E 01	470.	0.100E 01	475.	0.907E 00
480.	0.819E 00	485.	0.740E 00	490.	0.669E 00	495.	0.604E 00	500.	0.546E 00

DOSE AT DEPTH OF 70. MICRONS AVERAGED OVER AREA OF
RADIUS 5650. MICRONS IS 0.246E 01 RADS PER HR PER MICROCURIE

DOSE AT DEPTH OF 100. MICRONS AVERAGED OVER AREA OF
RADIUS 5650. MICRONS IS 0.137E 01 RADS PER HR PER MICROCURIE

DOSE AT DEPTH OF 70. MICRONS AVERAGED OVER AREA OF
RADIUS 495. MICRONS IS 0.321E 03 RADS PER HR PER MICROCURIE

This expression was used with several values of depth and area. For 70 microns depth and an area of 1 cm^2 (radius of 5650 microns), the averaged dose rate value is 0.24 rads per hour. If the area at this depth is reduced to 500 microns (corresponding to the range of the maximum energy beta-particle), the averaged dose rate value increases to 32 rads/hour.

Recent experiments with microspheres performed at LASL have shown that integrated doses of up to 50,000 rads to a small area of monkey skin have resulted only in a reddening of the skin without permanent damage. These doses are point doses at 100 micron depth. By comparison our computed single microsphere dose-rate at 100 microns is 400 rads per hour, or 67,000 rads per week.

E.3.2 Internal Exposure

The accepted maximum size of respirable particle is ~10 microns. Based on this premise the 20 micron microspheres are too large for inhalation. The natural rejection mechanism in the bronchial tubes and lungs, the cilia, will sweep a microsphere into the throat to be swallowed and to enter the digestive tract.

Another method whereby a microsphere may enter the body is by ingestion but, whether inhaled or ingested, the microsphere will enter the stomach and pass into the intestinal tract.

Most of the beta energy is likely to be absorbed by the contents of the stomach or intestinal tract. However, since the microsphere may be adjacent to the lining, and to be conservative in this analysis, it is assumed that no absorption occurs in the contents.

The analysis follows the treatment of K. Z. Morgan, et al.* Morgan treats (as Case 5) the inhalation of insoluble radioactive material where some portion of the GI tract is the critical body organ. The organs considered in the GI tract are listed in Table E-5.

TABLE E-5 PHYSIOLOGICAL PARAMETERS OF GI TRACT

GI Tract Organ	Mass (grams)	Effective Radius (cm)	Residence Time (hours)
Stomach	250	10	1
Small Intestine	1100	30	4
Upper Large Intestine	135	5	8
Lower Large Intestine	150	5	18
			Total = 31 hours

In the case of Pm-147, the long half-life of 2.6 years and the lack of any radioactive daughters of importance greatly simplifies the equation. The equation for the dose to an organ then has the approximate form:

$$\text{Dose in rads} = \frac{25.6\, Q f \bar{E}_\beta T}{m} \qquad \text{(E-17)}$$

where Q = quantity of Pm-147 in μc

$\bar{E}_\beta$ = average energy of beta-particle spectrum in Mev

T = residence time of material in organ in days

m = mass of organ in grams

f = fraction of inhaled material arriving in GI tract
For insoluble material, f is commonly taken to be 0.625;
for ingestion of a microsphere, f is 1.

In Table V of the cited reference the single exposure values of maximum permissible intake (MPI) for inhalation of insoluble radioactive material when the GI tract is the critical body organ are given. These values of MPI in microcuries will deliver 0.3 rem to the indicated organ during movement through the GI tract. Pm-147 is listed among many isotopes and the values are quoted here in Table E-6, column 2, for each of the four organs. These values can be obtained from Equation (E-17) by using a value of 0.3 rem for the dose, and 0.06 Mev for the average energy $\bar{E}_\beta$, along with the appropriate values om Table E-5.

* Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955, Volume 13, Page 139.

TABLE E-6 MPI AND RADIATION DOSE TO GI TRACT

GI Tract Organ	MPI for 0.3 rem (μc)	Dose from 0.1 μc Microsphere (millirem)
Stomach	1700	0.029
Small Intestine	1800	0.027
Upper Large Intestine	110	0.44
Lower Large Intestine	56	0.88

In column 3 of Table E-6, the dose value as imparted to each organ by a single microsphere containing 0.1 μc of Pm-147 passing through the GI tract is listed. These values were calculated by scaling the information in column 2. Comparison of the values indicates that the large intestine receives virtually the total dose and this total dose is less than two mrem.

There is a possibility that the microsphere withstands reentry heating in a partially ablated condition. As a result a microsphere may have diminished enough in size to enter the lungs and remain there as an insoluble particle. The equation which gives the integrated dose to the lung is given by:

$$F = \frac{C_f}{T_1 \lambda_{eff}} \left[\frac{1 - e^{-\lambda_R T_1}}{\lambda_R} + \frac{e^{-\lambda_{eff} T_2 (1 - e^{\lambda_B T_1})}}{\lambda_B} \right] \qquad \text{(E-18)}$$

in which

F = integrated dose to the lungs

$C_f = \frac{51.2\, f \times [EF(RBE)N]}{m}$

T_1 = inhalation time (day)

T_2 = period over which the dose is integrated to obtain the integrated dose (day)

λ_{eff} = effective decay constant of the radionuclide being considered (day^{-1})

$\lambda_{eff} = \lambda_R + \lambda_B$

λ_R = radiological decay constant (day^{-1})

λ_B = biological decay constant (day^{-1})

f = the fraction of the activity inhaled that reaches the critical organ

$EF(RBE)N$ = effective energy deposited in the organ by the radionuclide in question, including any daughter products (Mev)

m = mass of the critical organ (gram)

Upon substitution of the appropriate values for the above factors, the integrated dose to the lungs (F) for 0.1 μc of Pm-147 is ~55 mrem.