Considerations for Control of Radiation Exposures to Personnel from Shipments of Radioactive Materials on Passenger Aircraft

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Radiation Programs

CONSIDERATIONS FOR CONTROL OF RADIATION EXPOSURES TO PERSONNEL FROM SHIPMENTS OF RADIOACTIVE MATERIALS ON PASSENGER AIRCRAFT

Office of Radiation Programs
Environmental Protection Agency
Washington, D.C. 20460

December 1974

FOREWORD

The use of radioactive materials in nuclear medicine and other areas has increased rapidly in the past several years with the result that many shipments of these materials exist in general commerce every day. Shipments of radioactive materials on passenger aircraft are increasing at a rate of 15-25% annually. While most of these packages contain either very small quantities of radioactive materials or materials which exhibit little or no penetrating radiation, it has been estimated that a significant number emit enough radiation that exposure to the travelers aboard these aircraft could be a high percentage of the current Federal radiation protection guidance. Additionally, because of several incidents in recent years involving the shipment of such materials, various Federal agencies have conducted studies to determine the nature and extent of this problem.

Because of the responsibility vested in EPA (42 USC 2021h) for radiation directly or indirectly affecting health, including guidance to Federal agencies in the formulation of radiation standards, EPA has examined the question of exposure of passengers aboard commercial aircraft. The results of this examination are contained in this report, along with a recommendation on exposure levels that should be incorporated into the regulations of those Federal agencies charged to regulate conditions under which radioactive materials can be transported. The approach used in this instance, as well as any other circumstance involving radiation exposure of the U.S. population, has been to carry out EPA's basic responsibility to assure public health protection. This responsibility is carried out within the broad precedents established by the former Federal Radiation Council whose functions and responsibilities were transferred to the Environmental Protection Agency in 1970. This report was developed with information and comments provided by the Department of Transportation, the Federal Aviation Administration, the Atomic Energy Commission, and the Public Health Service, all of which have responsibility and expertise relative to transportation of radiation materials. We hope that the report will serve to communicate to the public the basis for our recommendation as to what constitutes reasonable protection of travelers on commercial aircraft.

Comments on this analysis as well as any new information would be welcomed; they may be sent to the Director, Technology Assessment Division (AW-559), Office of Radiation Programs, U.S. Environmental Protection Agency, Washington, D.C. 20460.

W. D. Rowe, Ph.D.
Deputy Assistant Administrator
for Radiation Programs

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I. INTRODUCTION AND BACKGROUND

The number of packages of radioactive material shipped on passenger aircraft annually has increased rapidly over the past few years and is estimated at about 800,000 (1) each year, a number that is expected to increase even more. While most of these packages contain either very small quantities of radioactive materials or materials which exhibit little or no radiation external to the package, a certain fraction of the packages contain radioactive materials which have significant external radiation for which protection must be provided. It has been reported that shipments of the radiopharmaceutical source, known as a molybdenum-technetium (Mo-Tc) generator, currently make up the majority of these shipments for which radiation protection is required (2). The Society of Nuclear Medicine (2) estimated that about 80,000 of these Mo-Tc generators were shipped in 1972. The shipment of radioactive materials for all purposes has been growing at a rate of 15 to 25% annually (3). Because of the relatively high energy of Mo-99 gamma rays and the number and frequency of shipments, Mo-Tc generators are generally regarded as the most significiant radiopharmaceutical, in terms of potential exposure to aircraft travelers, routinely shipped on passenger aircraft. Other shipments which have a potential for external radiation exposure include Ra-226, I-131 and Sn-In-113 generators. However, according to the AEC (7), almost all of the packages with a TI (exposure rate in mrem per hour at 3 feet from the surface of the package) greater than three which are transported on passenger aircraft are Mo-Tc generators. Thus, shipments of these generators produce the greatest exposure to aircraft travelers and control efforts should be directed to these shipments.

As a result of an incident involving leakage of a shipment of a source quantity of Mo-Tc by passenger aircraft in 1971 (3), the Atomic Energy Commission initiated investigations (4)(5)(6) to determine the nature and extent of the potential problem of shipping radioactive materials on passenger aircraft. The results of these investigations indicated that while the majority of flights on which radioactive materials were carried had no discernible radiation exposure to passengers, on some flights passengers were exposed to rates ranging from 20 to 25 mR/hour. These high exposure rates were apparently due to noncompliance with loading and spacing requirements on the aircraft. In a further analysis (7) of the problem the AEC determined that population doses (about 1,400 person rem per year) were comparable to other man-made sources of exposure to the general public but that individual doses to certain aircraft passengers who travel frequently could be as high as 160 to 170 mrem per year. Thus, in assessing the exposure of passengers, there is a need to examine both individual and selected population groups exposures. It is the purpose of this report to consider radiation protection factors for shipment of such material on aircraft and to provide recommendations for the radiological protection of passengers. The analysis will consider costs and effectiveness of various protection measures in order that the most efficiacious balance can be gained between the medical benefits of these materials and exposure of the air-traveling public.

Nearly all radioactive materials being shipped on commercial aircraft are shipped from one installation licensed by the Atomic Energy Commission to another with a similar license. The packages must meet specific requirements prior to leaving a licensed installation and must receive detailed inspection and satisfy other requirements during unpackaging and use. In shipment between these two licensed installations, the current regulatory policy of the U.S. Department of Transportation is that such materials be packaged in a way that they can move in normal commerce. These requirements specify type and quantities of radioactive materials (permitted for shipment in such normal commerce). The DOT regulations also specify exposure rate limits for packages submitted for shipment to provide protection from external radiation as follows:

Package Label Category	Exposure rate on accessible surface of package (mR/hour)	Exposure rate 3 feet from external surface of package (TI)(mR/hour)
Radioactive - White I	0.5	0
Radioactive - Yellow II	10	0.5
Radioactive - Yellow III	200	10

Current DOT regulations permit all three categories to be shipped on passenger carrying aircraft. The greatest reduction to individual passenger exposure would be gained by eliminating shipments of Radioactive-Yellow III packages. Elimination of the shipment of Radioactive-Yellow II packages would provide a slight additional reduction to individual passenger exposure and elimination of Radioactive-White I would have no significant effect because of the negligible external rate limit. Most of the Mo-Tc generators used by hospitals for radionuclide diagnostic examination are currently shipped on passenger aircraft as Yellow-III packages. Prohibiting shipments of Yellow-III packages would complicate procedures of the nuclear medicine industry unless options are available such as additional package shielding, ground transport, cargo aircraft shipments, or combinations of these to allow shipments of the required material to be made. This report examines the degree to which these actions can be reasonably applied to reduce dose to passengers during shipment primarily of Yellow-III packages.

Reductions of dose to personnel on aircraft can also be gained by prohibiting shipment of long-lived radioactive materials which could be shipped by other transport systems such as truck or rail. It is unlikely that an effective means of transport could be provided for long distance shipments for radionuclides with half-lives of less than about one week. Since Mo-Tc generators have a half life of 2.8 days, shipment of many of these generators on aircraft is generally necessary. These sources are the principal contributor of radiation exposure to individuals on aircraft; thus this mechanism of solving the problem alone can hardly be used. The approach is viable, however, for reducing needless radiation exposure to aircraft passengers from the shipment of long-lived radionuclides.

II. APPLICABLE RADIATION PROTECTION PRINCIPLES

The Federal Radiation Council (8), in May of 1960, promulgated guidance to Federal agencies for protection of the public from ionizing radiation. The recommendations of the National Council on Radiation Protection and Measurements (NCRP) (9) are consistent with the FRC guidance. The functions of the FRC were transferred to the Environmental Protection Agency in 1970; therefore, the basis for control of radiation exposure of the traveling public is the current Federal guidance which contains numerical guides and other principles. The various principles applicable to Federal agencies relevant to this problem area are as follows:

1. "Under the working assumptions used, there can be no single 'permissible' or 'acceptable' level of exposure, without regard to the reasons for permitting the exposure. The radiation dose to the population which is appropriate to the benefits derived will vary widely depending upon the importance of the reason for exposing the population to a radiation dose."

2. "Also, under the assumptions used, it is noted that all exposures should be kept as far below any arbitrarily selected levels as practicable. There should not be any man-made radiation exposure without the expectation of benefit resulting from such exposure. Activities resulting in man-made radiation exposure should be authorized for useful applications provided the recommendations set forth in this staff report are followed. Within this context, any numercial recommendations should be considered as guides, and the need is for a series of levels, each of which might be appropriate to a particular action under certain circumstances."

3. The FRC expanded this concept as ". . . This report introduces the use of the term Radiation Protection Guide (RPG). This term is defined as, the radiation dose which should not be exceeded without careful consideration of the reasons for doing so; every effort should be made to encourage the maintenance of radiation doses as far below this guide as practicable." For individuals in the population the RPG is 0.5 rem per year whole body dose; where the individual whole body doses are not known the recommended whole body dose protection guide for a suitable sample of the population is 0.17 rem per year.

4. "The Federal agencies should apply these Radiation Protection Guides with judgment and discretion, to assure that reasonable probability is achieved in the attainment of the desired goal of protecting man from the undesirable effects of radiation. The Guides may be exceeded only after the Federal agency having jurisdication over the matter has carefully considered the reason for doing so in light of the recommendations . . ."

5. The Administrator is responsible for following the activities of the Federal agencies in this area and promoting the necessary coordination to achieve an effective Federal program.

In accordance with the above basic guides, the use in medicine of many of the radionuclides shipped on aircraft is beneficial to society. It is well known that patients benefit directly from such procedures and improvements are continously being made to offer more beneficial procedures using radiation and radioactive materials to the public. The costs of producing, processing, shipping, and using medical radioisotopes are included in the price charged the patient. Therefore, the patient, who is the individual receiving the benefit, bears the monetary cost involved and a clear mechanism exists for having incremental costs of increased protection of all personnel involved passed on to the beneficiary. Shipments of radioisotopes involve radiation exposure of the general public and transportation industry workers who receive no offsetting benefit except the assurance that society has this medical service available. In this instance it appears reasonable that an examination of the shipment of radioactive materials used in medicine contrast the risks that the general public must bear against a placement of incremental costs for risk minimization on those who receive the benefits. An additional factor that should be satisfied is that methods of radiation dose reduction be both technically and economically feasible.

When examining a component of a broader problem area, it is important to assure that actions aimed at reducing doses within that component do not produce the same or higher radiological impact elsewhere because of adjustments that may result. This consideration is especially important in transportation of radioactive materials where several other modes of transport are available which may result in higher exposures to selected groups such as cargo handlers, travelers, or to the population because of longer times in transit, more frequent handling, etc.

To the degree possible, it is appropriate to consider established procedures, regulations, and other protective measures in alternate approaches to reduce radiation exposure in order to assure that any resulting changes will be at the minimum possible to achieve the desired goal. In this examination considerable recognition is given to the form of regulations established over the years by the Department of Transportation for shipments of hazardous materials. These regulations for radioactive materials are based on labeling, shielding, integrity, and placement of packages; thus the alternatives examined include these factors which have been proven to allow straightforward and effective regulatory and compliance requirements.

As mentioned earlier it is also important to recognize that in establishing exposure limits consideration must be given to population groups as well as individuals. However, because of the limited population being exposed at any given time from a shipment on an aircraft, the problem of control for this mode of transportation appears to require emphasis on protection of individuals. This possibility was borne out by the AEC (7) analysis in which it was estimated that the annual population dose was about 1,400 man rem and annual doses to individual passengers were estimated to range as high 170 mrem/year. Since the dose is normally due to external radiation fields, there is no persistent dose commitment that needs to be considered. Therefore, in this situation it is accepted that protection of individuals will provide adequate protection for any population passenger groups.

III. TECHNICAL ANALYSIS

A. Alternative Approaches to Reduce Passenger Exposure

Several alternatives are available to reduce the radiation exposure to passengers on aircraft. While not all options are feasible, the following are expected to be potential approaches for passenger protection: (1) additional shielding of packages, (2) placement options on aircraft, and (3) modified shipping procedures. The principal alternative analyzed in detail is additional shielding. It is believed that examination of this alternative brings out data on costs and effectiveness of most common controls to allow a determination of a means for reducing exposures to aircraft passengers to a range that can be found acceptable. It is apparent that a combination of these alternatives could be developed and implemented to reduce the dose received by aircraft passengers. Such a combination might be (1) ground transportation for closeby shipments, (2) increased package shielding for longer shipments necessitating air transport and (3) elimination of all packages labelled radioactive-yellow III with half lives greater than 30 days (except radiopharmaceuticals) from passenger carrying aircraft.

Additional Shielding of Packages

By using additional shielding, the package TI will be reduced and smaller radiation doses (corresponding to common practice, dose= dose equivalent herein) will be received by passengers. In order to evaluate additional packaging shielding cost as a function of dose rate in the passenger compartment, our analysis was made making use of data provided by the AEC (7). The AEC data were based principally on data reported by Brownell (14).

The cost effective analysis for additional shielding was based on lead shielding for a standard 500 mCi Mo-99-Tc-99m source which is the largest generator currently shipped. Dose rates due to the Mo-Tc generator were based on a source strength of 2485 mCi since the unit is typically shipped on Saturday morning. Mo-Tc generators were chosen for the analysis because they are probably the most dosimetrically significant of the radiopharmaceuticals shipped on passenger aircraft. Lead was chosen as the shielding material for the analysis since it is currently employed in packaging shielding. Brownell (14) also evaluated depleted uranium and tungsten shields and found these shields comparable in cost if they were returned to the manufacturer with credit given to the customer.

Dose rates in mrem/hr-100 mCi at one meter from the surface of the package containing the Mo-Tc generator as a function of lead thickness were based on Brownell's data (14). Mallinckrodt and New England Nuclear package size parameters were employed. Values of TI as a function of lead thickness appropriate for a 2485 mCi Tc-99m generator are presented in Figure 1.

The TI values in Figure 1 were converted to a dose rate at the seat location using methods derived by the AEC (7) for a package located on the floor of the cargo compartment directly below the seat. The results are shown in Figure 2. A transmission factor "Fo" of 0.7 was utilized for all packages in this analysis. The vertical height of the generator package was assumed to be 35.6 cm consistent with the container used by the New England Nuclear Corporation. The separation distance from the top of the package to the floor of the passenger compartment was obtained by subtracting the package height from the distance between the floors of the cargo and passenger compartments. Since the DC-9 cargo compartment configuration indicates higher seat location dose rates for a given lead thickness, this passenger aircraft was examined in detail in succeeding calculations as a limiting case. Since the generator package was assumed to be on the floor of the cargo compartment, the other passenger aircraft with larger distances between the passenger and cargo floors had smaller estimated dose rates at the seat location for any given shielding thickness.

The five aircraft considered here account for almost 90% of shipments of radioactive materials which exhibit penetrating radiation (7). In addition, these five aircraft also represent a size spectrum of aircraft currently used for passenger transport. Thus, the cargo compartment dimensions of the DC-9 (the limiting case here) would be expected to be similar to those of other smaller aircraft, such as the B-737 and the BAC-111, and dose rates calculated using the dimensions of the DC-9 would be approximately the same for these other aircraft.

Figures 1 and 2 were utilized to compute seat location dose rates as a function of appropriate TI values for the DC-9. The results for selected TI values are presented in Table 1. For example, a 5.35 cm lead shield is required to reduce the TI to 1 for the evaluated 2485 mCi source. At a TI of 1, the DC-9 seat location dose rate is approximately 0.49 mrem/hr; at a TI of 0.5 the dose rate is approximately 0.25 mrem/hr.

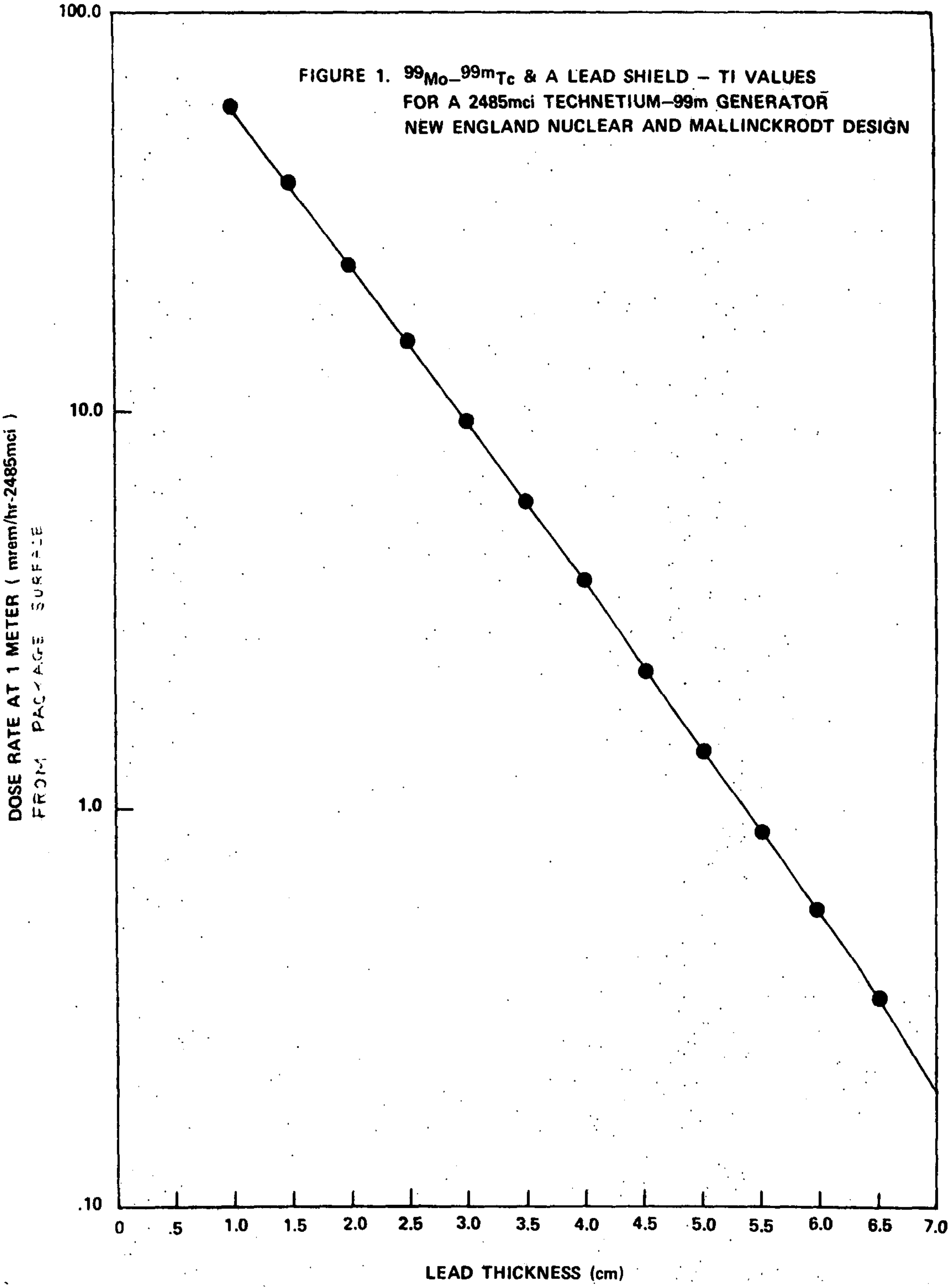


FIGURE 1. ^{99}Mo–^{99m}Tc & A LEAD SHIELD – TI VALUES FOR A 2485mci TECHNETIUM–99m GENERATOR NEW ENGLAND NUCLEAR AND MALLINCKRODT DESIGN

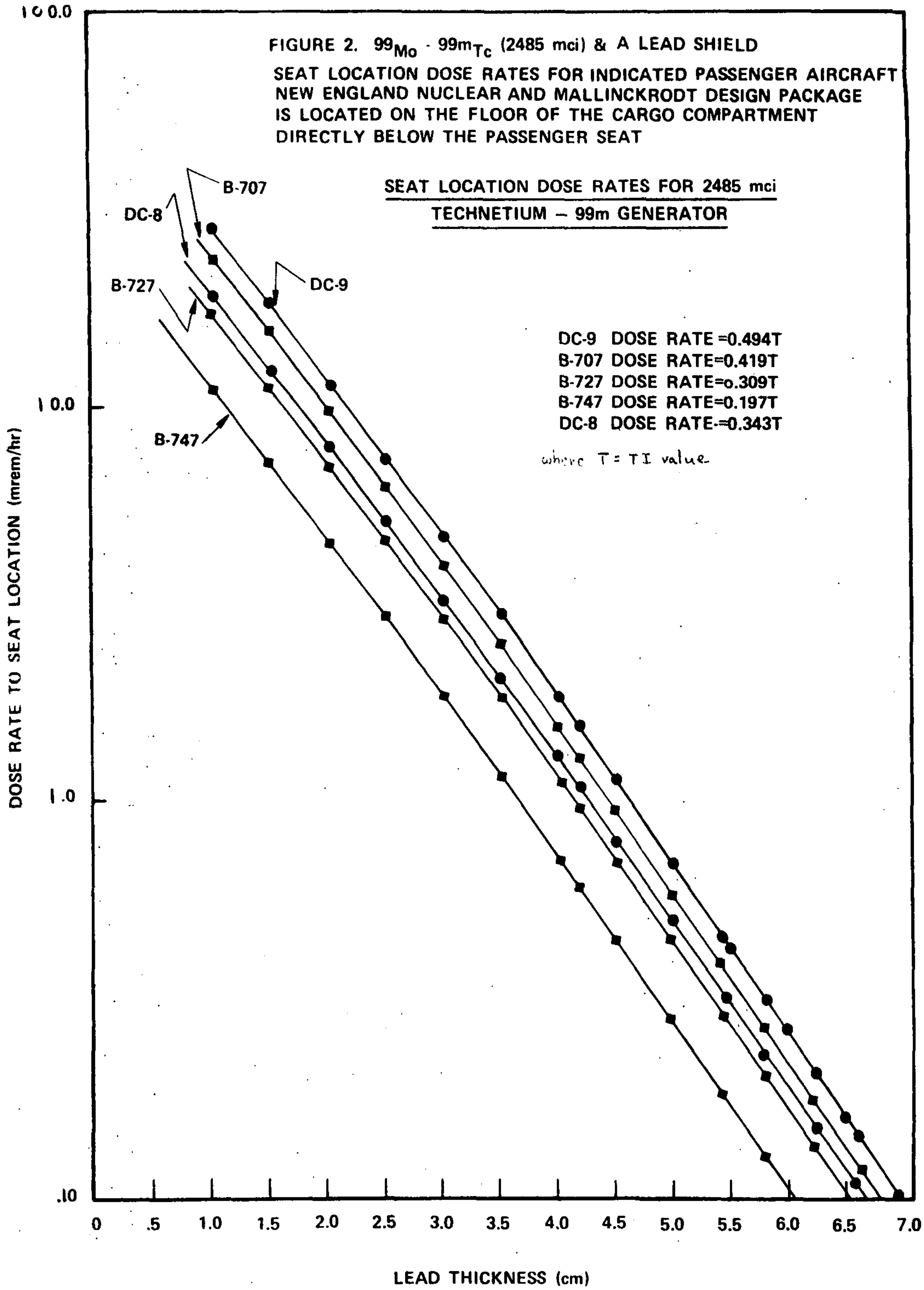


FIGURE 2. 99Mo - 99mTc (2485 mci) & A LEAD SHIELD
SEAT LOCATION DOSE RATES FOR INDICATED PASSENGER AIRCRAFT
NEW ENGLAND NUCLEAR AND MALLINCKRODT DESIGN PACKAGE
IS LOCATED ON THE FLOOR OF THE CARGO COMPARTMENT
DIRECTLY BELOW THE PASSENGER SEAT
SEAT LOCATION DOSE RATES FOR 2485 mci
TECHNETIUM – 99m GENERATOR
B-707
DC-8
DC-9
B-727
B-747
DC-9 DOSE RATE =0.494T
B-707 DOSE RATE=0.419T
B-727 DOSE RATE=o.309T
B-747 DOSE RATE=0.197T
DC-8 DOSE RATE-=0.343T
where T = TI value
100.0
10.0
1.0
.10
DOSE RATE TO SEAT LOCATION (mrem/hr)
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
LEAD THICKNESS (cm)

Table 1. Seat Location Dose Rates for One Package in the DC-9 Cargo Compartment*

Approximate Transport Index Values TI (mrem/hr at 1 meter)	Seat Location Dose Rate (mrem/hr)
0.5	0.25
1	0.49
2	0.99
3	1.48
4	1.98
5	2.47
6	2.96
7	3.46
8	3.95
9	4.45
10	4.94

* 2485 mCi technetium-99m generator located on the floor of the cargo compartment directly below the passenger seat location.

Cost evaluations of additional shielding for one Mo-Tc generator package include the disposable lead shield cost, ground delivery cost, air freight (plus 5 per cent tax) cost and additional industrial plus hospital handling costs for shields weighing more than 70 pounds. Cost values were determined as a function of weight. The weight of the lead shield as a function of lead thickness for the Mo-Tc generator was determined by averaging the New England Nuclear and Mallinckrodt values given by Brownell. The results are shown in Figure 3. The use of New England Nuclear values would result in a lighter estimated shield weight. The average cost of the shield (materials plus fabrication) was determined to be $0.295 per pound. Delivery cost was determined to be $7 per package up to 65 pounds and an additional 10 cents per pound for amounts over 65 pounds. The package weight was assumed to be equal to the lead shield weight. These data and a weighted average air freight cost plus 5% tax (Boston rate) were based on Brownell's report. Incremental costs were made relative to a 25 pound, 3.55 cm thick lead shield, which appears to be the type most commonly used at the present time. The total incremental cost was determined by adding incremental costs as shown in Table 2. All simplifying assumptions made here were the same as those made by the AEC and Brownell with the single exception that no handling cost was added until the weight reached 70 pounds. The 70 pound limit is consistent with the maximum allowable weight for baggage on the per-piece plan commonly used by major commercial air carriers. Excess baggage charges are levied on single pieces of luggage weighing more than 70 pounds under the per-piece plan.

Cost effective curves (total incremental cost per package versus seat location dose rate) were developed from information in Table 2 and Figures 2 and 3. The cost effective curves for one Mo-Tc generator on the floor of the cargo compartment of various aircraft are presented in Figure 4. The inflection points in the cost effective curves are the result of non-linear dose reduction with additional shield weight and increased rate charges for ground and air delivery of the packages. A step function change also occurs as the result of added handling costs which were added for shields weighing more than 70 pounds.

Interpretation of the cost effective curve for the DC-9 aircraft in Figure 4 indicates that the seat location dose rate could be reduced to 0.5 mrem/hr for an additional cost of $11 per package relative to a 25 pound package; for $30 the dose rate would be 0.25 mrem/hr. The largest portion of the $30 cost is due to the additional $12.50 cost of handling which is added in one lump for shields weighing more

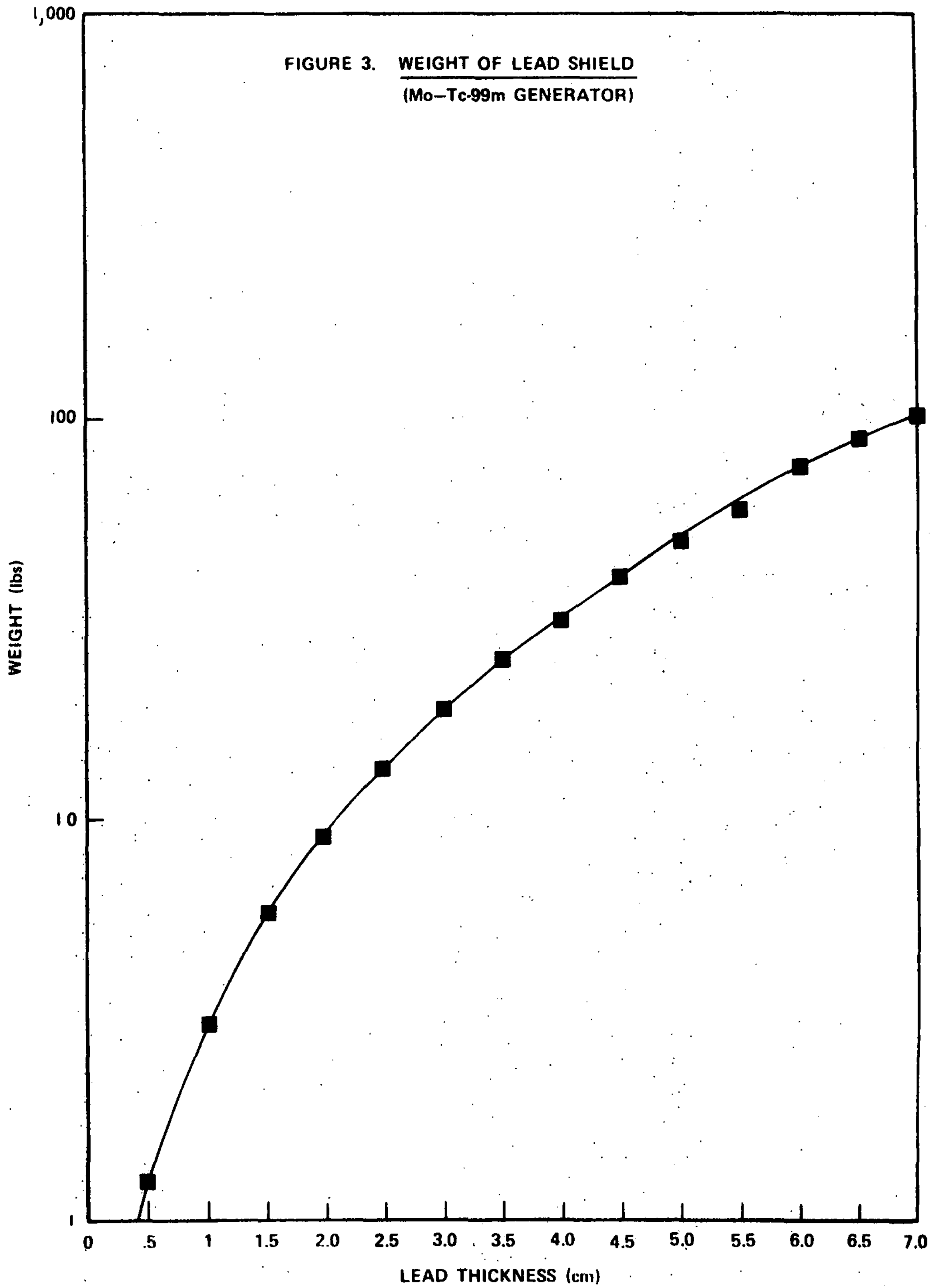


FIGURE 3. WEIGHT OF LEAD SHIELD
(Mo–Tc-99m GENERATOR)
1,000
100
10
1
WEIGHT (lbs)
0
.5
1
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
LEAD THICKNESS (cm)

Table 2. Incremental Costs (Dollars) Relative to a 25 Pound Package

	Incremental Costs(Dollars)				
Weight (lb)	Disposable Shield Cost	Ground Delivery Cost	Air Freight Plus 5% Tax (Boston Rate)	Industrial Plus Hospital Handling Cost	Total
25	0	0	0	0	0
30	1.47	0	0	0	1.47
34	2.65	0	0	0	2.65
35	2.94	0	0	0	2.94
40	4.42	0	0	0	4.42
50	7.37	0	1	0	8.37
60	10.32	0	2	0	12.32
70	13.27	.50	4	12.50	30.27
80	16.22	1	5	12.50	34.72
90	19.17	2	5	12.50	38.67
100	22.12	3	5	12.50	42.62

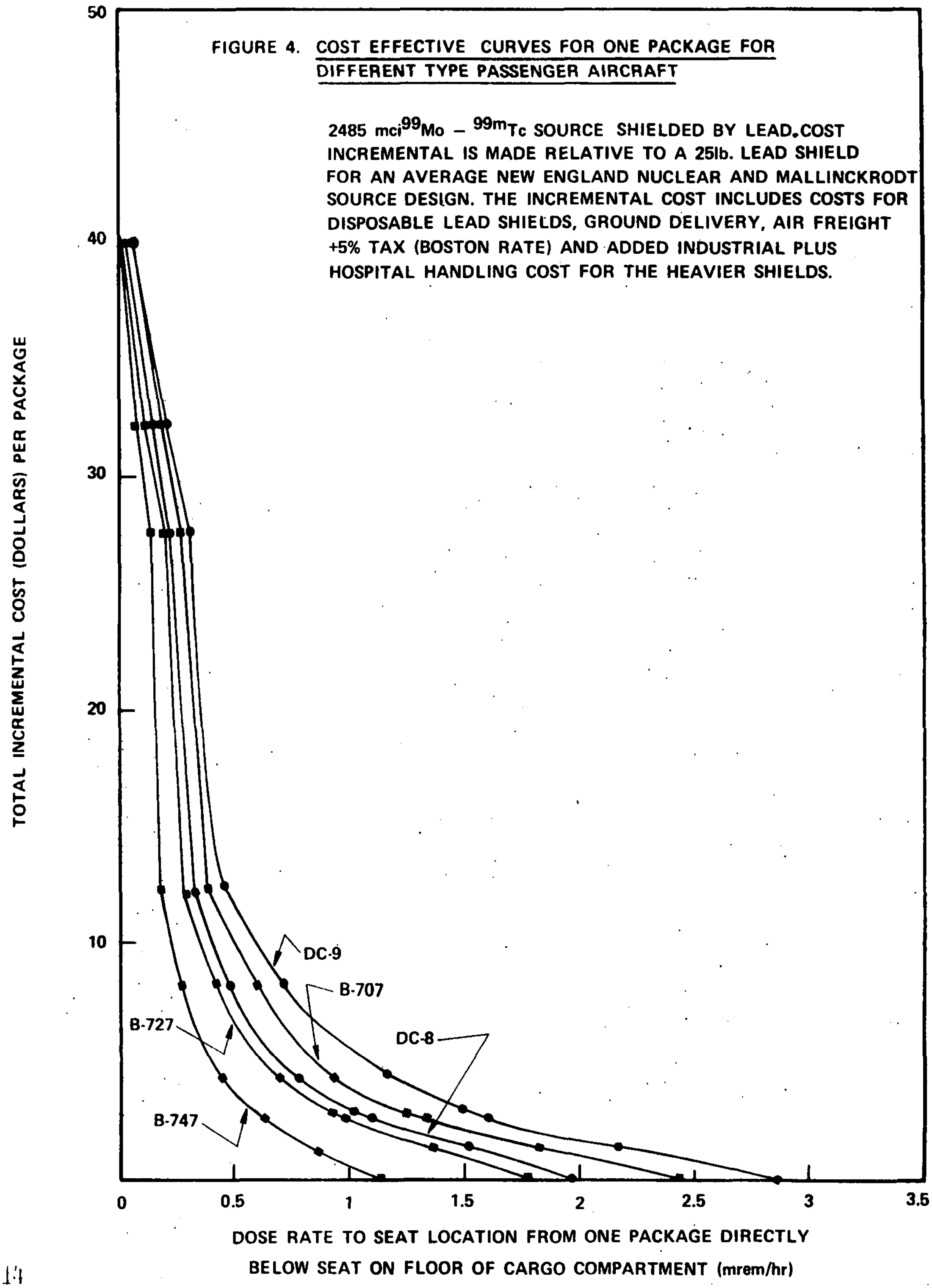


FIGURE 4. COST EFFECTIVE CURVES FOR ONE PACKAGE FOR DIFFERENT TYPE PASSENGER AIRCRAFT

2485 mci ^{99}Mo – ^{99m}Tc SOURCE SHIELDED BY LEAD. COST INCREMENTAL IS MADE RELATIVE TO A 25lb. LEAD SHIELD FOR AN AVERAGE NEW ENGLAND NUCLEAR AND MALLINCKRODT SOURCE DESIGN. THE INCREMENTAL COST INCLUDES COSTS FOR DISPOSABLE LEAD SHIELDS, GROUND DELIVERY, AIR FREIGHT +5% TAX (BOSTON RATE) AND ADDED INDUSTRIAL PLUS HOSPITAL HANDLING COST FOR THE HEAVIER SHIELDS.

than 70 pounds. If this handling cost were for shields above 85 pounds, the lower dose rate of 0.25 mrem/hr could be achieved at roughly twice the cost of the 0.5 mrem/hr rate. For any given package, the seat location dose rates would be lower for the other aircraft analyzed. If more than one package is stored in the cargo compartment, the seat location dose rate will obviously increase above those values presented in Figure 4 unless additional shielding is added or spacing is used.

Cost effective curves such as shown in Figure 4 are useful for displaying decision-making data in that they show the degree of efficiency of a control mechanism relative to the parameter being considered, in this case the cost. For example, the data in Figure 4 show that spending money on shielding to reduce the external dose rate becomes inefficient for exposure rates below 0.5 mrem/hr for the DC-9 aircraft. Such data do not, however, provide the criterion for a control decision, but by indicating the degree of efficiency in reducing the dose rate through expenditures for additional shielding, they become important to such a judgment. Other elements that should also be satisfied are the importance of the overall activity, who receives the benefits, who bears the risks, the distribution of risks and control costs, and whether controls would disrupt obtaining the benefits of the activity. If these factors are considered at the level of 0.5 mrem/hr, which is shown in Figure 4 to be the level below which controls based on shielding become inefficient, it is found that the beneficial activity will certainly continue, the costs will be minimal and will be borne by patients who receive the benefit, and the dose to passengers who are bearing the risk for essentially no direct benefit is cost effectively reduced. On the basis of these factors this control level is both technically and economically feasible.

The $11 cost increment represents an increase of about 4% of the $300 cost for a large Mo-Tc generator (400 to 500 mCi). The influence of incremental costs on diagnostic examinations can be based on information presented by the Society of Nuclear Medicine (2) that about 80,000 generators are used each year to perform 2.9×10^6 diagnostic procedures. At an incremental cost of $11 per shipment, each procedure will cost about $0.30 more; at a cost of about $30 the added cost would be about $0.90. These incremental costs are insignificant when compared to the typical costs of these diagnostic procedures which typically range between $100 and $150.

It is also possible to construct similar cost effective curves for reduction of population dose impact as a function of cost. For a given population size and number of packages such curves would have the same shape as those in Figure 4. Such information is important to control decisions if benefits and risks are generally distributed over a given population and a criterion is available to decide between risks and costs. The AEC determined that approximately 1,400 man-rems per year could be expected for a seat level dose rate equivalent of 2 mrem/hr maximum and 1 mrem/hr average from air shipments, and that reduction of this population impact would cost in the range of $1,000 per man-rem. Two important factors are involved that make it difficult to base control decisions on this projected population impact. First, risks are borne unknowingly by passengers for others who are clearly defined to receive the benefit of having the shipment occur. The passenger obtains no direct benefit; he may indirectly benefit by the fact that such procedures are available and he may one day need one. Second, when a suitable sample of individuals are likely to receive radiation doses approaching current exposure guides, the exposure of these individuals becomes the principal consideration in control decisions. Control of radiation exposure of passengers on commercial aircraft is, therefore, one of protecting the exposure of individuals and not the population.

A direct correlation exists between the seat location dose rate and TI's per package and TI's per flight. This relationship, which would be of importance to shippers and regulatory agencies in developing procedures is shown in Figures 5 and 10 for the DC-9 cargo compartment configuration. If more than one package is considered for a given seat location dose rate, the maximum TI per package would need to be reduced to meet any given dose rate criteria, however, the maximum TI per flight can be increased if spacing between the packages is utilized. The multiple package and spacing alternative is examined in a separate section of this paper.

A cost effective curve for the approximate maximum TI per package on a DC-9 is presented in Figure 6. The total incremental cost per package relative to a 25 pound package is shown to be $11 per package for a maximum TI per package of 1. Brownell determined an incremental cost relative to a 34 pound package of $17 per package to reduce the TI to 1. The cost of a large Mo-Tc generator (400 to 500 mCi) is about $300.

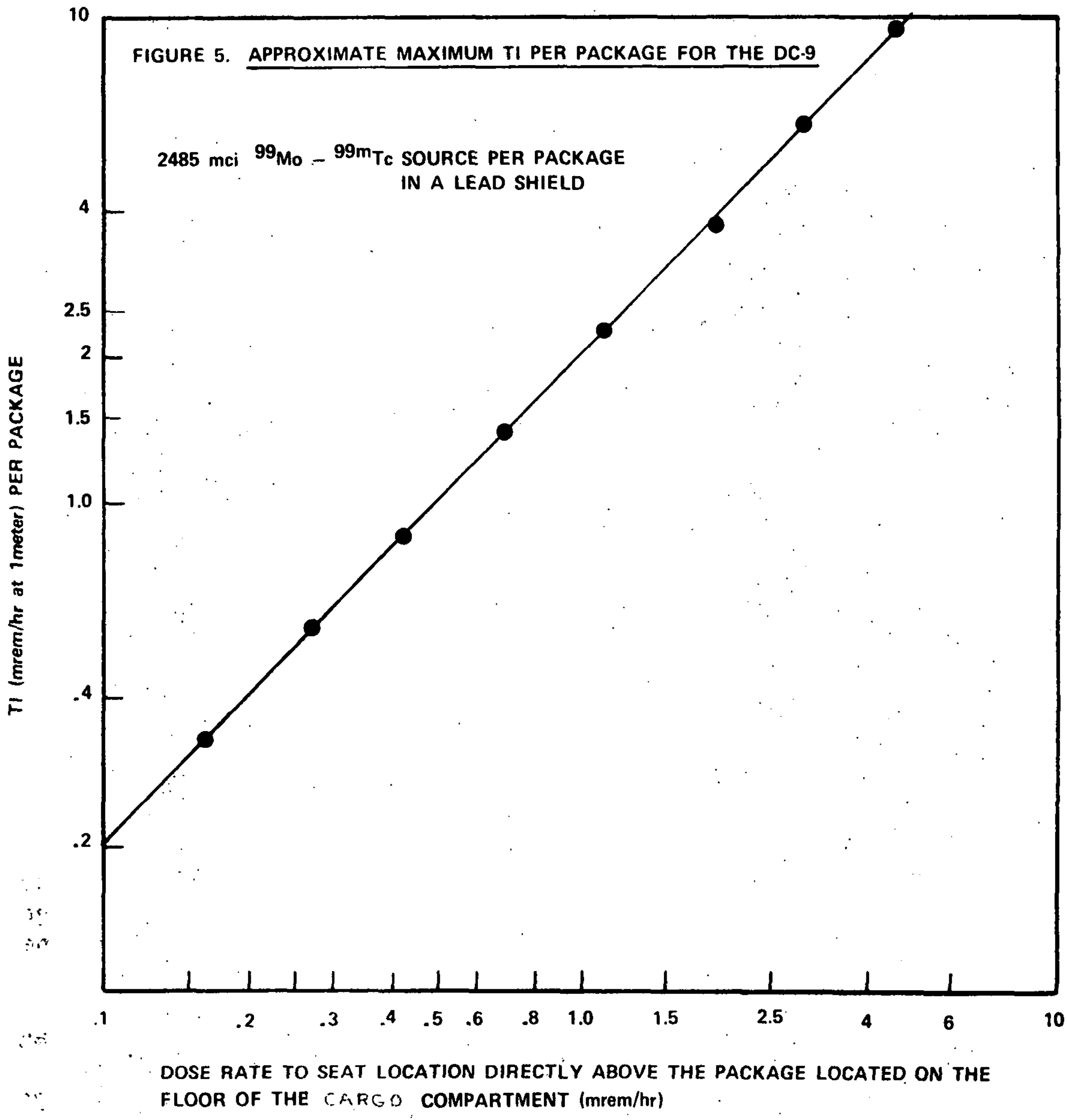


FIGURE 5. APPROXIMATE MAXIMUM TI PER PACKAGE FOR THE DC-9
2485 mci 99Mo – 99mTc SOURCE PER PACKAGE IN A LEAD SHIELD
TI (mrem/hr at 1meter) PER PACKAGE
10
4
2.5
2
1.5
1.0
.4
.2
.1
.2
.3
.4
.5
.6
.8
1.0
1.5
2.5
4
6
10
DOSE RATE TO SEAT LOCATION DIRECTLY ABOVE THE PACKAGE LOCATED ON THE FLOOR OF THE CARGO COMPARTMENT (mrem/hr)

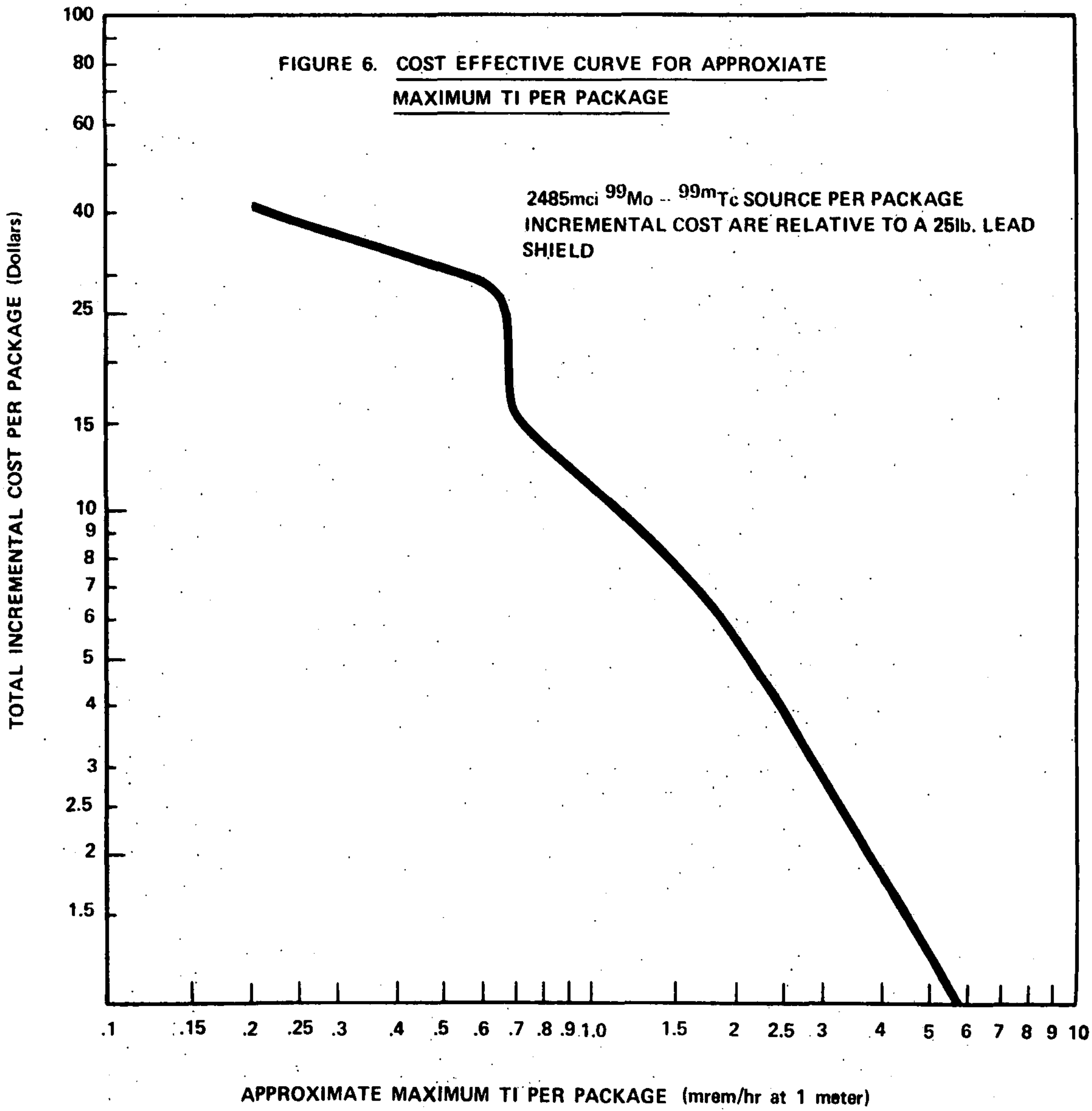


FIGURE 6. COST EFFECTIVE CURVE FOR APPROXIATE MAXIMUM TI PER PACKAGE

B. Effect of Package Placement on Passenger Exposure

1. Spacing of Individual Packages

Although package shielding directly influences seat location dose rate, the seat location dose rate is also influenced by the number and placement of additional packages in the cargo compartments of passenger aircraft. These factors are especially important relative to the maximum TI per package and the maximum TI per flight that would be allowed to meet any selected seat dose rate criteria. The dose rate from multiple packages is dependent on the spacing between packages.

The DC-9 has the smallest separation distance (of the evaluated passenger aircraft) between the floors of the passenger and cargo compartments so the placement option evaluation will be based on the limiting geometry of the DC-9. In the evaluation of spacing of multiple packages, the dose rate from three packages in the passenger compartment was considered. Three packages were chosen consistent with the AEC's conclusion that three packages contribute essentially all of the radiation dose at the seat location with the maximum radiation dose rate. The dose rate to the seat location when three packages of equal TI are loaded with one package directly below the seat and two packages loaded symmetrically at a spacing out distance (SOD) on either side of the center package were computed using the AEC model. All packages were assumed to be located on the floor of the cargo compartment. Assumptions for the parameters used in the analysis were the same as those used previously in the cost effective evaluation of additional packaging shielding. A vertical transmission factor of 0.7 and a generator package vertical height of 35.6 centimeters were assumed. TI values were taken from Figure 1 of this paper. The maximum seat location dose rates for three 2485 mCi Mo-Tc generator packages in the DC-9 cargo compartment are presented in Figure 7. Curves were drawn for SOD's of 0 cm, 70 cm, and 210 cm. A SOD of zero centimeters represents the worst case for three packages on the floor of the cargo compartment. A SOD of 210 cm was evaluated since this SOD was evaluated by the AEC (7). A SOD of 70 cm was evaluated as an intermediate case. Relative to the worst case of a SOD of zero, SOD's of 70 cm and 210 cm result in dose rate reduction factors for the maximum seat location of 1.39 and 2.26 respectively. It should be pointed out that these dose reduction factors may be difficult to realize in current cargo compartment loading practices. The difficulty in achieving compliance with spacing out distances is a strong argument against strong dependence on this alternative for achieving dose reductions to the maximum seat location in the passenger compartment.

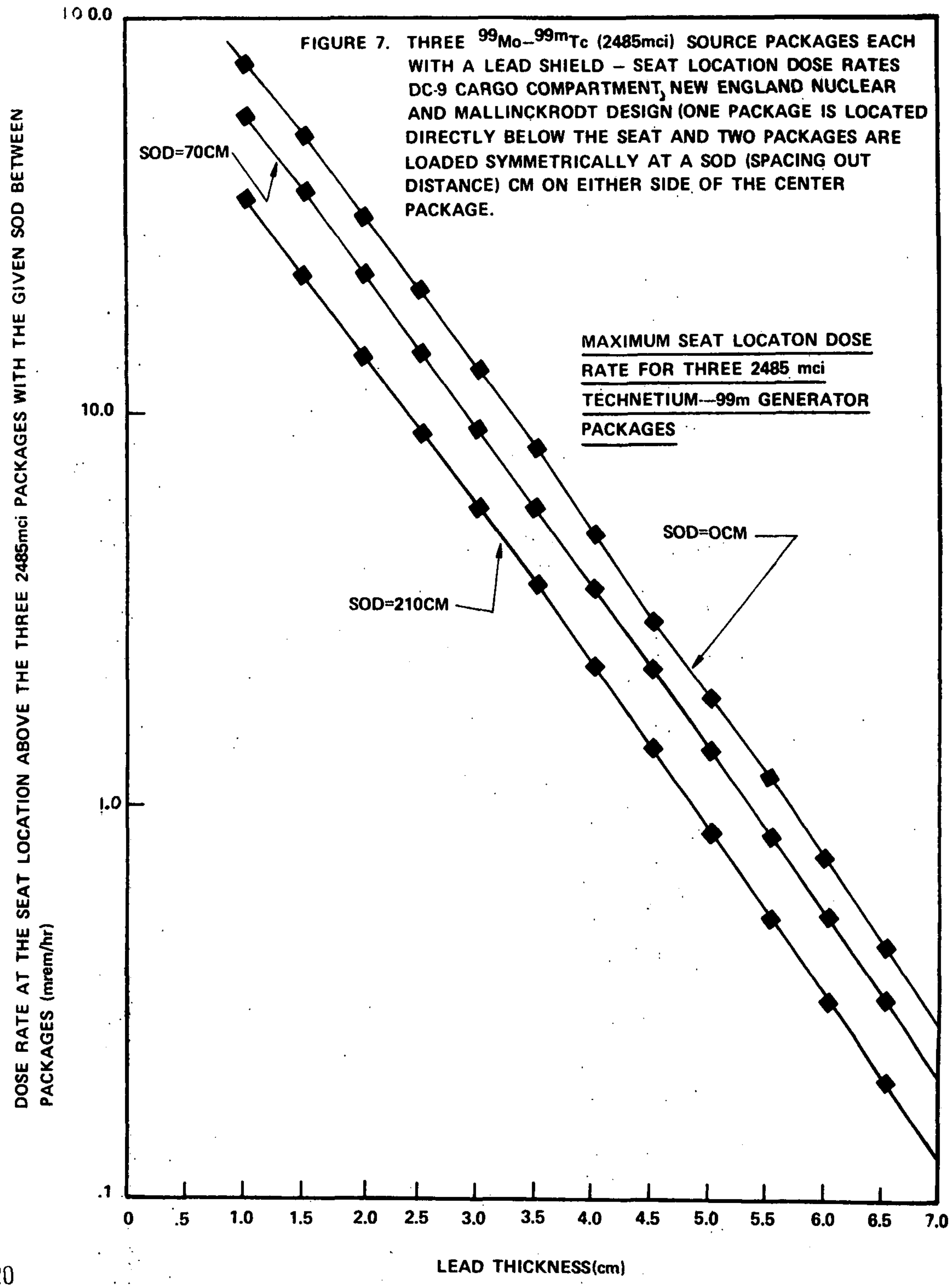


FIGURE 7. THREE 99Mo–99mTc (2485mci) SOURCE PACKAGES EACH WITH A LEAD SHIELD – SEAT LOCATION DOSE RATES DC-9 CARGO COMPARTMENT, NEW ENGLAND NUCLEAR AND MALLINCKRODT DESIGN (ONE PACKAGE IS LOCATED DIRECTLY BELOW THE SEAT AND TWO PACKAGES ARE LOADED SYMMETRICALLY AT A SOD (SPACING OUT DISTANCE) CM ON EITHER SIDE OF THE CENTER PACKAGE.
MAXIMUM SEAT LOCATON DOSE RATE FOR THREE 2485 mci TECHNETIUM—99m GENERATOR PACKAGES
SOD=70CM
SOD=0CM
SOD=210CM
100.0
10.0
1.0
.1
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
LEAD THICKNESS(cm)
DOSE RATE AT THE SEAT LOCATION ABOVE THE THREE 2485mci PACKAGES WITH THE GIVEN SOD BETWEEN PACKAGES (mrem/hr)

Deviations from the SOD during loading will significantly increase the maximum individual dose rate.

In order to cost effectively evaluate the spacing option on the DC-9 for three technetium-99m generator packages, the curves (total incremental cost per package versus seat location dose rate) shown in Figure 8 were developed for SOD's of 0, 70, and 210 centimeters. For an added cost of $11 per package (corresponds to incremental cost for a 57 pound shield plus freight) and a spacing out distance of 210 cm between packages, the maximum DC-9 seat location dose rate can be reduced to 0.6 mrem/hr. Without spacing between the packages, the maximum seat location dose rate is 1.6 mrem/hr for an added cost of $11.

In order to meet a given seat location dose rate criteria, maximum TI's per package and TI's per flight were determined for the DC-9 cargo configuration and the results are presented in Figures 9 and 10. Utilizing a maximum seat location dose rate of 0.5 mrem/hr and Figure 9 for evaluation purposes, the maximum TI per package for a DC-9 is 1 if only one package is stored in the cargo compartment. The maximum TI per package is reduced to 0.8 for three packages and a spacing out distance of 210 cm between packages. If spacing is not utilized, the maximum TI per package would have to be reduced to 0.35 in order for three packages to be carried on the DC-9 at a maximum seat location dose rate of 0.5 mrem/hr. Figure 10 shows that the total TI per flight for the DC-9 is reduced to one unless spacing is employed. If the TI/package is reduced to 0.8 and spacing between packages is utilized, the maximum TI per flight for the DC-9 can be increased to approximately 2.5. An analysis similar to that conducted for the DC-9 can be done for other types of passenger aircraft.

2. Package Placement in the Cargo Compartment

The dose rate to the seat location from one package in the cargo compartment is strongly dependent on where the package is located in the cargo compartment and slightly dependent on the package size. In order to evaluate the effect of package size, a sensitivity analysis was conducted for a package located on the floor of the DC-9 cargo compartment and a package located at the top of the DC-9 cargo compartment. The results of the sensitivity analyses are shown in Tables 3 and 4.

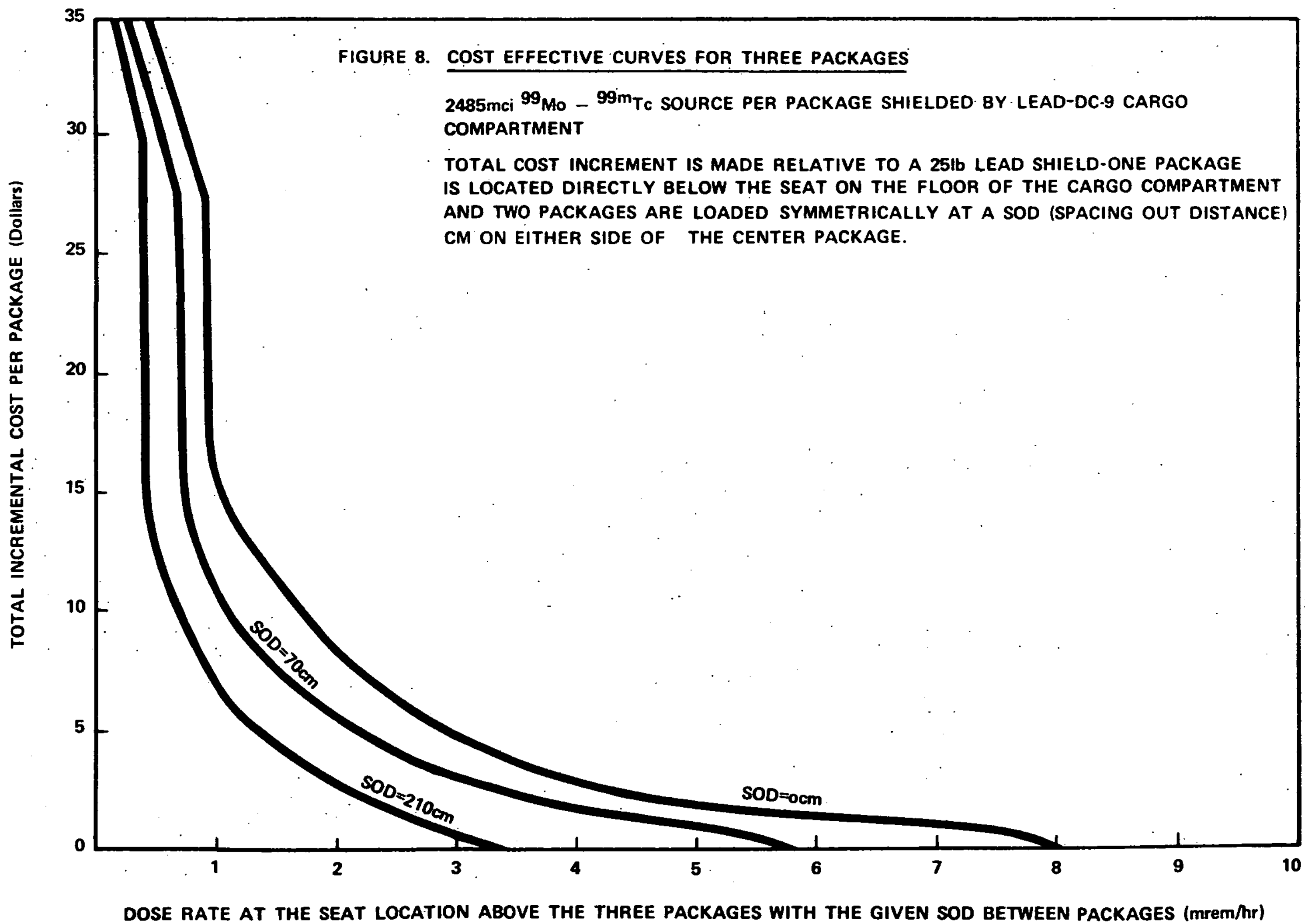


FIGURE 8. COST EFFECTIVE CURVES FOR THREE PACKAGES

2485mci ^{99}Mo – ^{99m}Tc SOURCE PER PACKAGE SHIELDED BY LEAD-DC-9 CARGO COMPARTMENT

TOTAL COST INCREMENT IS MADE RELATIVE TO A 25lb LEAD SHIELD-ONE PACKAGE IS LOCATED DIRECTLY BELOW THE SEAT ON THE FLOOR OF THE CARGO COMPARTMENT AND TWO PACKAGES ARE LOADED SYMMETRICALLY AT A SOD (SPACING OUT DISTANCE) CM ON EITHER SIDE OF THE CENTER PACKAGE.

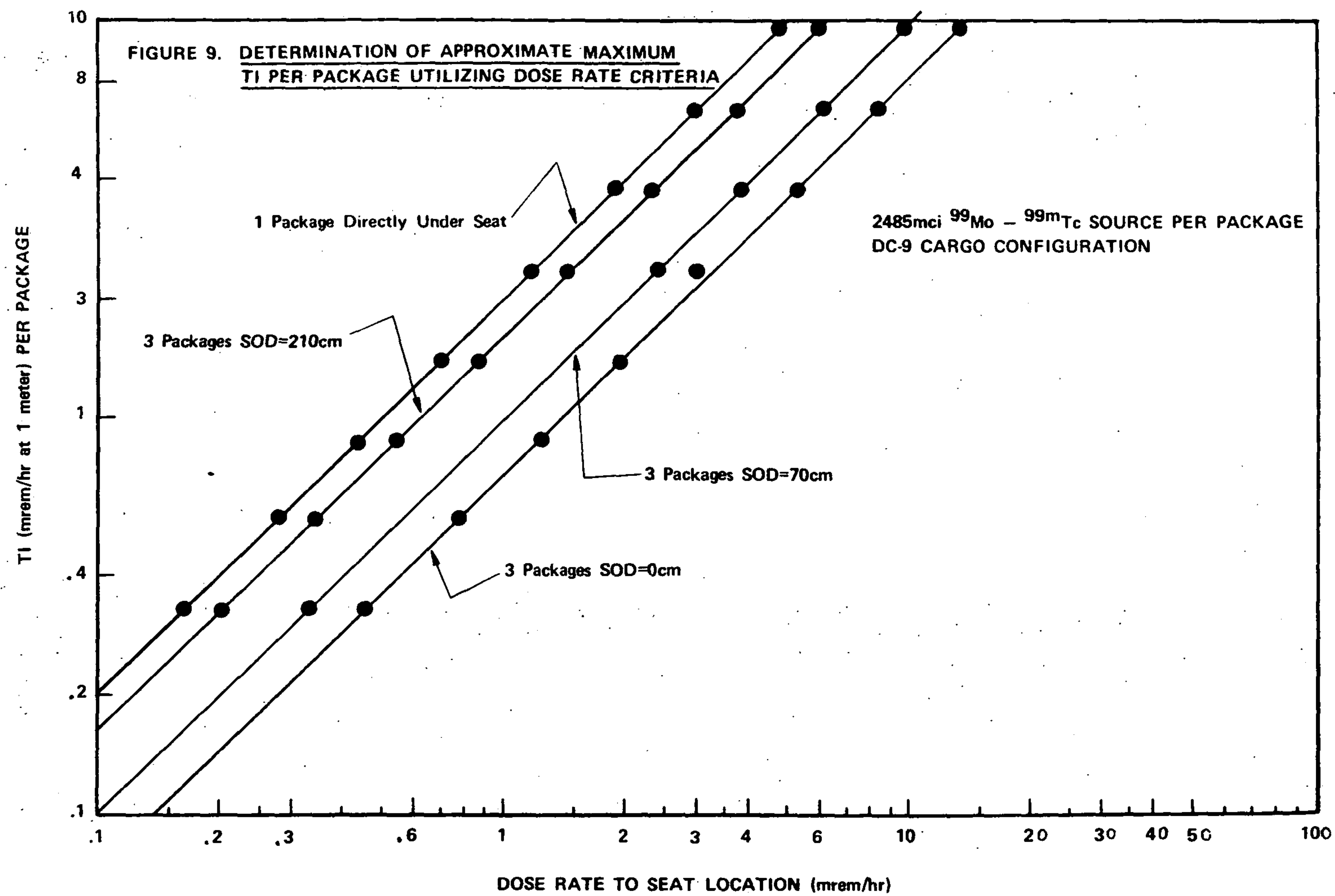


FIGURE 9. DETERMINATION OF APPROXIMATE MAXIMUM TI PER PACKAGE UTILIZING DOSE RATE CRITERIA

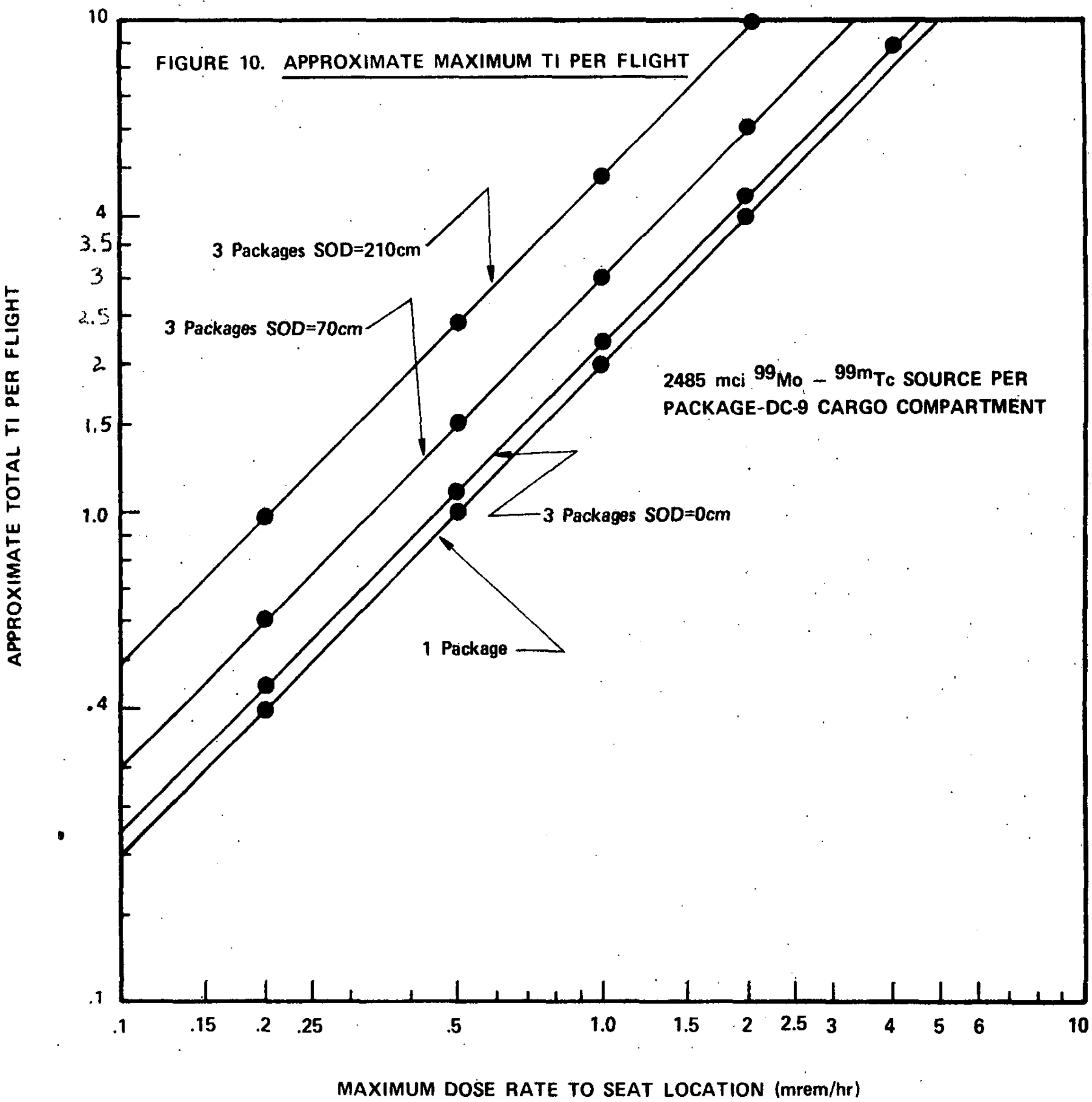


FIGURE 10. APPROXIMATE MAXIMUM TI PER FLIGHT
3 Packages SOD=210cm
3 Packages SOD=70cm
3 Packages SOD=0cm
1 Package
2485 mci ^{99}Mo – ^{99m}Tc SOURCE PER PACKAGE-DC-9 CARGO COMPARTMENT
APPROXIMATE TOTAL TI PER FLIGHT
MAXIMUM DOSE RATE TO SEAT LOCATION (mrem/hr)
10
4
3.5
3
2.5
2
1.5
1.0
.4
.1
.1
.15
.2
.25
.5
1.0
1.5
2
2.5
3
4
5
6
10

Table 3. Floor Location Package Size Sensitivity Analysis for the DC-9

Package Vertical Height (cm)	Approximate Maximum Seat Location Dose Rate Normalized to 1 for 40 cm (vertical height) package located on the DC-9 cargo compartment floor
15	0.84
20	0.87
25	0.90
30	0.93
35	0.97
40	1.0
50	1.1

Table 4. Top of Cargo Compartment Location Package Size Sensitivity Analysis

Package Vertical Height (cm)	Approximate Maximum Seat Location Dose Rate Normalized to 1 for a 40 cm (vertical height) package located at top of the cargo compartment
15	1.6
20	1.4
25	1.3
30	1.2
35	1.1
40	1.0
50	.85
55	.79

The floor location package size sensitivity analyses (Table 3) assumed that the package was on the floor of the cargo compartment and that the spacing between the floors of the cargo and passenger compartments was 118 cm. The seat location was assumed to be 40 cm above the floor of the passenger compartment. The maximum seat location dose rate was assumed to be proportional to $1/(40 + 118 + d/2)^2$. Since $d/2$ was much less than 40 + 118, package size "d" changes did not greatly change the seat location dose rate.

The package loading location which will result in the maximum seat location dose rate is the case where the package is located at the top of the cargo compartment directly under the floor of the passenger compartment. For this package location, the maximum seat location dose rate was assumed to be proportional to $1/(40 + d/2)^2$. The results in Table 4 indicate that the maximum seat location dose rate is more dependent on package size for a package located at the top of the cargo compartment than for a package located on the floor of the cargo compartment.

Utilizing the data in Tables 3 and 4, a comparison was made of the maximum seat location dose rate for a package on the floor and at the top of the DC-9 cargo compartment. The comparison results presented in Table 5 indicate that the maximum seat location dose rate increases significantly when the package is placed at the top rather than on the floor of the cargo compartment. If the package is loaded at the top rather than on the floor of the cargo compartment, the maximum seat location dose rates would be even greater for other types of passenger aircraft that have a greater separation distance between the floors of the passenger and cargo compartments. Passenger seat location dose rates will be greatly increased for packages located at the top of the cargo compartment above those loaded on the floor of the cargo compartment.

3. <u>Special Aircraft Compartments</u>

Radioactive materials could be shipped in passenger aircraft with low exposure to passengers if the material was placed in compartments designed specifically to provide protection. Two basic design philosophies are available for this alternative; first, the distance factor philosophy which would place the radioactive material at a sufficient distance from normally occupied compartments to maintain low exposure levels to occupants; and second, the shielding philosophy which would provide sufficient mass between the radioactive material and aircraft

Table 5. Maximum Seat Location Dose Rate Comparison For Different Cargo Compartment Loading Locations

Package Vertical Height (cm)	Approximate DC-9 Seat Location Dose Rate Ratio [Package at Top of Cargo Compartment / Package on Floor of Cargo Compartment]
15	10
20	8.8
25	7.8
30	6.7
35	6.0
40	5.3
50	4.2

Table 6. Weighted Exposure Time for Select Groups

Select Groups	Weighted Exposure Time Per Year (Hours)	
	Average	Maximum
Most frequent travellers	17	50
Weekday commuters	13*	125*
Weekend commuters	23	130

*The weighted exposure time includes a time reduction factor of 1/2 to account for the fact that the number of TI's on flights carrying radioactive material on weekdays is less than half the number on weekends.

Table 7. Weighted Exposure Time* for Passenger Who Sits in the Seat Location Having the Maximum Dose Rate

Trips/yr in Seat Location Having the Maximum Dose Rate	Weighted Exposure Time (Hours)	
	Maximum Dose Rate Time	Average Dose Rate Time
1	5	
2	10	(see table 6)
3	15	
4	20	

* Assumes 5 hours per trip

passengers to maintain a low exposure level to passengers. An example of the first case is a wingtip compartment which would provide a maximum spacing distance to passengers. The second case could be achieved through the use of a permanent lead shield in the cargo compartment in which all radioactive material packages would be placed for shipment.

Both of these cases would require a detailed analysis by aircraft designers to insure that the additional weight and/or structural requirements would not reduce or interfere with flight safety. The costs would also require close scrutiny since modification of essentially all aircraft currently in service would be required. In addition, this option introduces the regulatory issue of placing more of the protection requirements on the carrier rather than the shipper. However, this alternative could provide the additional protection indirectly and thus could be investigated thoroughly to determine its acceptability.

4. Restricted Seating Areas on Aircraft

The AEC has recommended that predesignated areas within the cargo compartment for all passenger aircraft be identified and used for storage of radioactive materials during shipment. An adjunct to this recommendation would be the identification of those seats at which the higher exposure rates would exist when radioactive materials were on board. The use of these seats could then be restricted on any or all flights in which radioactive materials are carried. This alternative appears feasible for those flights which have partial occupancy. However, when occupancy is at or near capacity, the cost of restricting the use of a group of seats could be high depending on the flight time. However, even if use of the restricted seats were permitted for under capacity or near capacity conditions, there would be some reduction in overall exposure because not all flights are at capacity. An estimate of the exposure reduction which could be attained if restricted seats were not used during flights of less than full capacity can be made by assessing data on flight occupancy factors in conjunction with data on the fraction of flights carrying radioactive material. This option may be worthy of investigation since the dose reduction would be achieved with no additional cost.

For either of the above cases a significant reduction in the dose to the embryo and the fetus could be accomplished by prohibiting the seating of fertile women in the restricted seats. This is due primarily to the higher radiosensitivity of the embryo and the fetus as discussed by the NCRP (9).

C. Effect of Shipping Procedures on Passenger Exposure

1. Modified Schedules for Mo-Tc Generators

It appears feasible to modify shipping schedules of the Mo-Tc generators to reduce the exposure rate to passengers. The first modification considered is the shipment of one Mo-Tc generator (500 mCi quantity) at 8 a.m. on Sunday rather than 8 a.m. on Saturday (14).

In order to have 500 mCi remaining at 8 a.m. on Friday, 1930 mCi should be shipped at 8 a.m. on Sunday. This includes a correction factor for radiological decay and 10% overage for elution efficiency and other factors. The attached Figure 11 presents cost effective curves for both the 1930 and 2485 mCi source strengths. If sufficient lead shielding is added to limit the maximum passenger seat dose rate (from one package) to .5 mrem/hr, a cost saving of $1.50 per package will result if the weekly shipment is made at 8 a.m. on Sunday rather than 8 a.m. on Saturday. If sufficient lead shielding is added to limit the maximum passenger seat dose rate (from one package) to .2 mrem/hr, a cost savings of $3 per package will result if the weekly shipment is made at 8 a.m. on Sunday rather than 8 a.m. on Saturday. The cost savings for other dose rate criteria can be determined from an analysis of Figure 11.

2. More Frequent Shipments of Smaller Mo-Tc Generators

A second alternative for shipment of Mo-Tc generators is to ship two sources per week instead of one. Such a change would reduce doses to the maximum individual but would not significantly reduce population dose.

This option requires twice as many shipments per week than the shipment of a single "500 mCi" source. In order to have 500 mCi at 8 a.m. on Wednesday and 500 mCi at 8 a.m. on Friday, 1520 mCi can be shipped at 8 a.m. on Saturday and 294 mCi can be shipped at 8 a.m. on Wednesday. If both the 294 mCi and 1,520 mCi shipments are made in 25 pound lead shields the dose rate to the seat location directly above the packages will not exceed 1.8 mrem/hour. These results are shown in Figure 12. The dose rate to the seat location from a 2485 mCi package

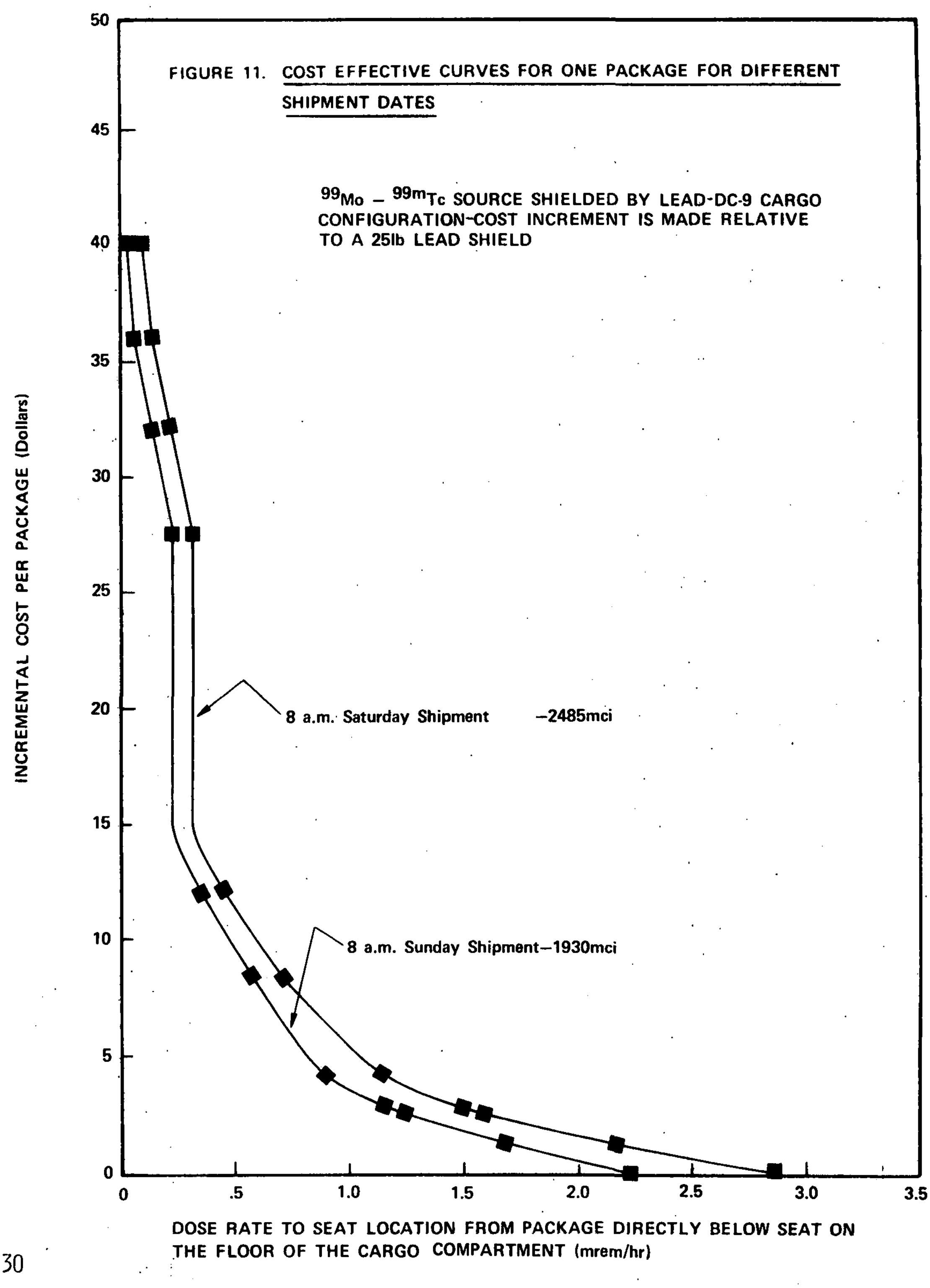
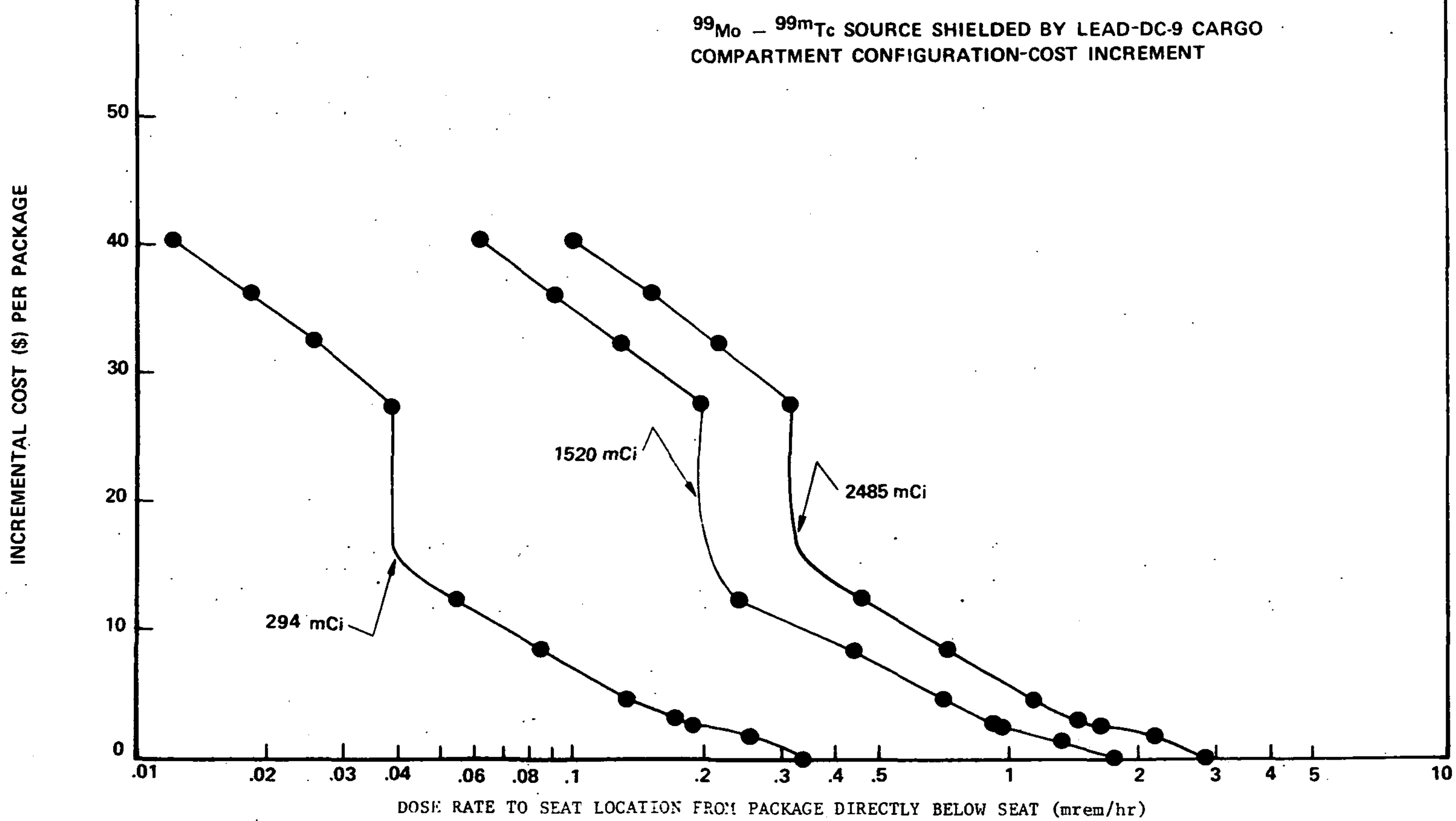


FIGURE 11. COST EFFECTIVE CURVES FOR ONE PACKAGE FOR DIFFERENT SHIPMENT DATES
99Mo – 99mTc SOURCE SHIELDED BY LEAD-DC-9 CARGO CONFIGURATION-COST INCREMENT IS MADE RELATIVE TO A 25lb LEAD SHIELD
8 a.m. Saturday Shipment –2485mci
8 a.m. Sunday Shipment–1930mci
INCREMENTAL COST PER PACKAGE (Dollars)
DOSE RATE TO SEAT LOCATION FROM PACKAGE DIRECTLY BELOW SEAT ON THE FLOOR OF THE CARGO COMPARTMENT (mrem/hr)
50
45
40
35
30
25
20
15
10
5
0
.5
1.0
1.5
2.0
2.5
3.0
3.5

FIGURE 12. COST EFFECTIVE CURVE FOR ONE PACKAGE (OPTION ANALYSIS OF BREAKING THE 2485 mci PACKAGE UP INTO 2 PACKAGES 1520mci AND 294mci



in a 25 pound shield is 2.9 mrem/hr. By breaking up the 2485 mCi source into two packages and maintaining the same shielding, the dose rate is lowered from 2.9 to 1.8 mrem/hour at the expense of doubling the shipping costs since two packages rather than one had to be shipped per week.

The general conclusion from this analysis is that it does not appear cost effective to break the shipment up into several packages weighing 25 pounds or less. It costs less dollars for greater mrem/hr reduction to add shielding to one package. The reason it costs more to break the large shipment up into smaller shipments is that <u>ground delivery and air freight charges are the same up to some minimum weight</u> (40 lb. for air freight and 65 lbs. for ground delivery). The delivery charge is the same for both a five pound and a forty pound package. In addition, there is the cost of two shields instead of one.

3. <u>Tc-99m Shipments Instead of Mo-Tc Generators</u>

Shipments of Tc-99m could be made instead of the Mo-Tc generators. Because of the half-life of Tc-99m it would be necessary to ship on a daily basis and thus there would be five shipments per week instead of one. However, the Tc-99m has a much lower photon energy and this can be shielded with a much smaller quantity of materials to bring the external dose rate down to well within 0.5 mrem/hour at one meter for a 2,500 mCi shipment.

The cost per package shipped is estimated at $3 for a lead shield, $7 for ground delivery and $10 for air freight for a total of $20 per shipment or $100 per week. This cost can be compared to the weekly costs for Mo-Tc generator shipments of $27.50 for a 25 pound shield and $39.82 for a 60 pound shield neither of which would include the cost of preparing the Tc-99m sources at the producer's facility as compared to the cost of preparing the Mo-Tc generator.

It appears the greatest problem associated with this alternative is assurance of daily delivery of the Tc-99m to the user. While a system for rapid delivery probably exists in many areas, routine rapid delivery services undoubtedly are not available for many areas or are prohibitively expensive. In addition, areas which suffer frequent disruption in transportation services because of inclement weather or other causes could be ill served.

Shipments of Tc-99m could supplement Mo-Tc generators and thus potentially reduce the quantity of material shipped via the generators while still assuring a supply of Tc-99m for medical use. This alternative may offer the industry an economic means of meeting passenger exposure criteria for selected situations especially when combined with other procedures. Its actual use would probably need to be established over time by the various industry segments weighing timing, costs, convenience, and other factors.

4. Surface and Air Cargo Shipments Instead of Passenger Aircraft Shipments

Mo-Tc generators could be shipped by surface (truck) or air cargo flights only or a combination of these two options. Several scenarios could be developed as to what methods or combinations of methods would provide adequate service and what the costs would be. This alternative appears to offer the greatest risk reduction since the major source of passenger dose is the shipment of Mo-Tc generators (7) and these passenger exposures would be reduced to practically zero.

The AEC estimated that the cost of shipping via truck was approximately $10 per package more than the cost via passenger aircraft and that the cost on cargo aircraft was the same. This higher cost for truck shipment is probably a significant reason why it is not used more and air shipment is chosen in the largest number of cases. Certainly for distances of a few hundred miles, trucks would assure 48 hour delivery of shipments. The incremental cost of shipping by surface would be only about 3% of the current cost of generators ($300) and would be only $0.28 per patient examination (2).

While the shipment of Mo-Tc generators via surface or cargo aircraft would undoubtedly complicate the delivery of this radiopharmaceutical in some areas of the country, it is not immediately evident that the practice of nuclear medicine would be significantly affected. Since the principal producers of Mo-Tc generators are geographically distributed, it appears quite feasible that they would be able to adequately serve by truck most users in their vicinity within the two to three day period currently used in shipping by passenger aircraft. It is also reasonable to assume that maximum exposures to individuals would be less since these individuals would be located at much greater distances and, in most cases, their exposure times would be less. It is concluded that this alternative appears feasible and should be investigated in much more detail.

D. Annual Dose Estimates

Although any given limitation on a seat location dose rate serves to limit passenger exposure for a given trip, it is important to consider the implications of such practices on annual dose. Number of trips, seating choice, frequency of shipment, and hours flown are large determinants of annual passenger dose. The AEC devised a model relating these factors to convert dose rate to an annual dose. Weighted exposure times in hours per year based on this model are presented in Table 6 for select groups. The indicated weighted exposure times reflect select group flying habits and representative radioactive traffic factors. These times are based on 500 hours flown each year, reduced by assumed probabilities of what chance a flight will have radioactive material on it and what chance a selected traveler will select the seat with the maximum dose rate. Probabilities were assumed for maximum probable conditions and average conditions.

Both maximum and average weighted exposure times are presented in Table 6. The average seat location dose rate which is assumed as 1/2 the maximum dose rate consistent with the AEC recommendation was utilized to compute the dose rate for those situations where an individual does not sit in the seat having the maximum seat dose rate. The average dose rate was multiplied by the appropriate weighted exposure time in Table 6 to obtain an annual dose. It should be recognized that the computed dose may be somewhat conservative in that it is basically the surface entrance dose rather than an average whole body or gonadal dose. All packages are assumed to be placed on the floor of the cargo compartment.

The annual dose to the passenger who sits in the seat location having the maximum dose rate can be computed based on the number of trips per year the passenger sits in the seat having the maximum dose rate. Using the assumptions of the AEC model, the weighted exposure time for this passenger for 1, 2, 3, and 4 trips per year in the seat location having the maximum dose rate is presented in Table 7.

In order to illustrate the use of the exposure time data in Table 6 and 7, the annual dose for select groups was computed, as shown in Table 8, for maximum seat location dose rates of 0.5 mrem/hr and 0.25 mrem/hr. The average dose rate in the aircraft was assumed to be half these rates. It must be recognized that the data in Table 8 are based on the assumptions that all aircraft on which radioactive materials are shipped will have the same maximum seat location dose rate when material is shipped and that the traveler will occupy the seat for 5 hours when he randomly selects it.

Table 8. Annual Doses to Select Groups Based on Indicated Maximum Seat Location Dose Rates

Select Group	Trips per Year Sitting in Seat Having Maximum Dose Rate	Annual Dose (mrem)*			
		for 0.5 mrem/hour		for .25 mrem/hour	
		Average	Maximum	Average	Maximum
Most frequent traveller	0	4.2	12	2.1	6.2
Most frequent traveller	1	6.8	14	3.4	7.4
Most frequent traveller	2	9.2	17	4.6	8.7
Most frequent traveller	3	12	20	5.9	9.9
Most frequent traveller	4	14	22	7.1	11
Weekend commuter	0	5.8	32	2.9	16
Weekend commuter	4	16	42	8	21
Weekday commuter	0	3.2	31	1.6	16
Weekday commuter	4	13	41	6.5	21

* Assumes that maximum seat dose rate is the same on all passenger aircraft which transports radioactive material that traveller could select and that when he selects seat with maximum dose rate, he would occupy it 5 hours.

With such circumstances Table 8 indicates that a weekend commuter may receive, for a seat dose rate of 0.5 mrem/hr, an annual dose of up to 42 millirem, of which 10 millirem comes from occupying the seat for 5 hours on 4 different trips. If industrial shippers were to choose, as could reasonably be expected, to meet a dose rate criterion of, say, 0.5 mrem/hr by standardizing to a shield that would meet the criterion for the limiting aircraft (in this case the DC-9), then shipments on other aircraft could be expected, as shown in Figure 4, to have seat dose rates less than 0.5 mrem/hr. Since only about 16% of shipments are on DC-9 aircraft, but a large fraction (about 50%) are on B-727 aircraft where dose rates for packages with the same shielding would be less, it is unlikely that this annual dose of 42 millirem would occur. Also, since the limiting case is based on a DC-9 aircraft which is generally used for relatively short trips (usually one to two hours) the assumption of seat occupancy is quite conservative. When account is given, therefore, for lower maximum seat dose rates on other aircraft on which the largest fraction of shipments occur and realistic seat occupancy times, it is reasonable to expect, for packages shielded and placed to limit the maximum seat dose rate of 0.5 mrem/hr, that the dose per trip would be about one millirem and the largest annual dose to selected frequent travelers would be less than 25 millirem. These doses are believed to be protective of sensitive groups in the population such as children and pregnant females who travel infrequently, and are comparable to other well controlled sources which expose the public to radiation.

The health risk to an individual from cancer is minimal at exposure levels that would result in doses to indivudals of less than 25 mrem/yr. Based on U.S. vital statistics, the probability that an individual will die of cancer is about 0.19. After a lifetime irradiation at 0.025 rem per year (in excess of background radiation) this probability is increased by about 0.0002, which is the best estimate based on the geometric mean of absolute risk (.0001) and relative risk (.0004). This represents an increase of about one tenth of one percent. This is not the total impact from lifetime total body exposure; the NAS-BEIR Committee (10) estimates the total of both fatal and non-fatal radiation induced cancers would be a factor of 2 larger. Genetic effects are more difficult to estimate; but their total increase, expressed over several generations, would be comparable to the increased cancer incidence.

E. Impact on Other Exposures

Since it appears that the most efficacious approach to reduce exposures to personnel aboard passenger aircraft is to increase packaging shielding, it is expected that exposures to all personnel involved in handling packages and many of those using sources would be reduced to an extent similar to that for personnel aboard aircraft. The impact of an attempt to reduce exposure aboard aircraft is not expected to result in a transference of radiation dose to other personnel in other parts of the transportation industry since procedures, storage awaiting shipment, schedules, and number of times handled would not be expected to change from the current situation. The possible exception to this is diversion of the majority of shipments to surface transport in lieu of developing increased package shielding and placement requirements. In this instance, the general public will still quite likely receive less exposure since the demand for most of the materials precludes their being in transit for long periods and the fact that the alternative modes of transport (trucks principally) do not also transport passengers.

IV. SUMMARY AND RECOMMENDATION

This analysis indicates that a number of technically and economically feasible actions can be taken to reduce the radiation doses received by personnel on passenger aircraft from radioactive materials which, because of short half lives or urgent medical needs, are required to be shipped by air. These actions allow the public to derive the full benefits of nuclear medicine, are not expected to produce additional radiation impact on other members of the population, and are consistent with current air transport regulations based on package labeling, quantities, and placement requirements. The actions to obtain such radiation dose reductions will result in additional monetary costs; however, there are cost-effective levels available which result in minimal increases in the total costs to patients for nuclear medicine procedures. A cost-effective level of dose rate reduction based on case corresponds to an increased cost of about $0.30 to a patient who normally pays $100 to $150 for the procedure. Such a dose rate reduction can be gained for the limiting aircraft by increasing package shielding from the 25 pounds currently used to about 58 pounds, an action that corresponds to a TI of 1.0 for Mo-Tc generators and a maximum seat level dose rate of 0.5 mrem/hr on the limiting aircraft. Shipment of such packages on the types of passenger aircraft available are expected to result, whith appropriate credit given to occupancy and travel time, in doses to the travelling public of about one millirem per trip and less than 25 millirem to those who travel frequently. Achievement of such exposures is protective of public health and is in accord with principles contained in current Federal radiation guidance.

On the basis of the foregoing analysis, it is recommended that necessary transportation of radioactive materials on commercial aircraft be conducted in such a manner that the dose equivalent rate at seat level to any occupant of an aircraft does not exceed 0.5 mrem/hr.

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