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Contract Program or Project Title: Generic Environmental Assessment on Transportation of Radioactive Materials Near or Through a Large Densely Populated Area

Subject of this Document: Transport of Radionuclides in Urban Environs: A Working Draft Assessment

Type of Document: Preliminary Report
Draft Assessment

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Date of Document: May 1978

Responsible NRC Individual and NRC Office or Division: N. Eisenberg
Transportation and Product Standards Branch
Office of Standards Development

This document was prepared primarily for preliminary or internal use. It has not received full review and approval. Since there may be substantive changes, this document should not be considered final.

Sandia Laboratories
Albuquerque, New Mexico 87185

for the

U.S. Department of Energy

Prepared for
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

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TRANSPORT OF RADIONUCLIDES IN URBAN ENVIRONS: WORKING DRAFT ASSESSMENT

Prepared for
U.S. Nuclear Regulatory Commission

by

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ABSTRACT

The purpose of this study is to assess the environmental impacts from transportation of radioactive materials in urban environs. The impacts from accident-free transport, vehicular accidents during transport, and from other abnormal situations are analyzed. The approach is outlined including description of the models developed and the data bases emloyed to account for the special features of the urban environment. The operations and contributions of the task group formed to assist in this study are also discussed. The results obtained for the New York City study area are presented and explained.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge Corinne M. Henning, Leo S. Gomez, and Peter E. McGrath for their assistance in editing this study.

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CHAPTER 1

OVERVIEW

1.1 Background of Study

On May 10, 1976, work was initiated by Sandia Laboratories for the Nuclear Regulatory Commission (NRC) to assess the environmental impacts resulting from the transportation of radioactive materials through urban areas. An interim report was issued by Sandia on April 29, 1977 in connection with that work which contained an explanation of initial assessment methodology.[1] This Working Draft Assessment contains preliminary results obtained from the models developed and perfected since that time. It is expected that this document will largely be the basis for the Draft Environmental Impact Statement to be issued by the NRC later this year.

This environmental impact assessment therefore forms a part of the technical basis for the NRC consideration of possible rule changes in 10 CFR 71 and 73--those NRC regulations pertaining to the transportation of radioactive materials. Radiological, nonradiological, and economic environmental impacts were considered. The investigation uses a risk methodological approach similar to that in NUREG-0170,[2] a study on the transportation of radioactive material throughout the United States, but reflects detailed consideration of the special characteristics of urban areas as they affect all transport of radioactive materials.

1.1.1 Chronology

On March 3, 1977 the NRC announced in the Federal Register[3] its intention to prepare a generic Environmental Impact Statement (EIS) on the transportation of radioactive materials in urban areas.

Sandia Laboratories had been selected for this work and had already begun the investigation to supply the NRC with the requisite environmental impact assessment. As explained to Sandia by the NRC, the urban study was not in response to specific or prospective rule changes, but was associated with the initiation of rule-making proceedings announced June 2, 1975 concerning air transportation of radioactive materials.[4] This environmental assessment on transportation of radioactive materials in urban areas was envisioned as providing the NRC with additional information on the expected environmental impacts produced by all radioactive material shipments through densely populated areas.

Also germane to the background of this study is the question of local or federal jurisdiction over shipments of radioactive material through large cities, as exemplified by New York City. On January 15, 1976, an amendment was passed to the New York City Health Code restricting shipment of certain categories and quantities of radioactive materials into and through the city.[5] The shipments restricted include plutonium, highly-enriched uranium, and spent fuel. The question of federal preemption[6] of local control in these matters was still under litigation at the time of this writing.

Sandia proposed early in the study that, in view of the diversity of opinion in this area and the wide scope of both technical and non-technical concerns, a task group of knowledgeable individuals from outside the NRC and Sandia be established to assist in obtaining a more comprehensive and useful environmental impact assessment. The NRC approved this approach by providing funds for public meetings and other expenses incurred by the task group.

The Task Group on Transportation of Radioactive Material in Urban Environs, formed by Sandia, is composed of twenty individuals from industry, and from governmental and environmental areas. Public meetings of this task group were held September 20, 1976 in New York City, November 16 and 17, 1976, in Arlington, Virginia, March 29 and 30, 1977 in Baltimore, Maryland, and July 13 and 14, 1977 in Houston, Texas. In addition to these meetings, certain task group members assisted in the review of the social impacts aspect of the assessment in meetings held September 1, 1977 in Houston, Texas, and January 5, 1978 in Albuquerque, New Mexico.

With the preliminary development of the assessment methodology and required computer programs, and inputs from the task group, an interim report on the study was issued April 29, 1977.[1] This interim report contains a detailed description of the radiological consequences model, outlines the methods being used to estimate transport and dispersion of released material in an urban environment, and reviews other key facets of the technical programs being developed to ascertain the quantifiable environmental impacts resulting from the transportation of radioactive materials in urban areas. The interim report was reviewed by the task group at the Houston meeting and also discussed at the Advisory Committee on Reactor Safeguards (ACRS) Working Group meeting on Transportation of Radioactive Material held August 23, 1977 in New York City.[7]

1.1.2 Purpose

The purpose of this report is to assess the environmental impacts resulting from the transportation of radioactive materials in urban environs. Of particular interest to this investigation are the quantification of the effects on these impacts of the special features of urban areas not treated in detail by previous studies. These features include: high population densities, shielding effects of buildings, the effects of local meteorology on accident consequences, detailed routing in cities, and diurnal variations in population. The complex, composite effect of these and other urban-specific factors on the radiological and other environmental impacts owing to transportation of radioactive materials could not be reasonably estimated prior to an analysis of the type described in this report.

An additional aim of this work is to produce a generic environmental impact analysis, i.e., one which is general enough to produce results which are inclusive of urban areas in the United States. This generic basis of the study does not mean that every city in the United States must be treated in the detailed calculations, rather that the model used on the archetypal urban area analyzed should possess characteristics which are parametric to U.S. cities.

The principal objective of this report is to furnish the NRC with the preliminary results of this environmental assessment so that they and other agencies on the federal, state, and local levels can better judge whether any reasonable modifications need to be made in the present regulations to minimize the perceived environmental impact. It is, of course, recognized that the NRC will consider other aspects of cost and benefit to the general public in undertaking any future changes in the regulations affecting transportation of radioactive material in urban areas.

1.1.3 Scope

The scope of the work represented in this report encompasses the estimation of the radiological, nonradiological, and economic environmental impacts resulting from the transport of radioactive materials in urban areas. Radiological impacts include possible human health effects such as genetic effects, early fatalities, early morbidities, and latent cancers produced from exposure to ionizing radiation. Nonradiological impacts include social impacts, such as socially expressed perceptions of the benefits and detriments of the shipment of radioactive material. Other nonradiological impacts relate to the additional accidental injuries and deaths attributable to movement of radioactive materials by exclusive-use vehicles. Nonradiological impacts in the form of health effects can also result since many of the materials being shipped are chemically toxic. A variety of significant economic impacts can occur consequent to spillage of radioactive material in urban areas, such as land-use denial and decontamination costs.

The environmental impacts considered result from accident-free transport of radioactive materials in urban areas, from vehicular accidents involving transporters of the material, from human errors in packaging or deviations from quality assurance, and from purposeful sabotage or diversion of the radioactive material shipments or transporting vehicles.

In accident-free transport, nothing unusual happens to the radioactive material packages or transporting vehicles. No radioactive material is therefore released from containment and no loss of shielding occurs. Radiological impacts result from the exposure of nearby people to external penetrating radiation emitted from the material and passed through the packaging and other intervening shielding.

Accidents involving vehicles moving the radioactive material can damage packaging and result in dispersal of the radionuclides and subsequent inhalation by, or direct exposure to, surrounding population. Vehicular accidents can also damage or totally remove radiation shielding and thereby produce higher than normal exposure to penetrating radiation. Delays at an accident site or slow accident response can aggravate the situation, thereby producing larger environmental impacts. Substantial economic losses can also derive from these situations.

Human errors in labeling, packaging, or in deviations from quality assurance practices can produce environmental impacts which are similar to, but usually less severe than, those produced by vehicular accidents.

Sabotage, because of its deliberate aspects, has the potential to produce large releases of material, resulting in radiological and economic impacts on the scale of severe accidents. Theft or diversion of radioactive material also has the potential for producing significant environmental impacts via the planned movement of the material to places where large consequences may be expected.

The scope of this study applies to the transport of all radioactive materials in urban areas, excepting those related to weapons, weapon components, or shipments on military vehicles. Materials investigated include radiopharmaceuticals such as Technetium-99m and Iodine-131, used in the diagnosis of disease and location of tumors.[2] High energy gamma-ray emitters such as Cobalt-60 are used in the radiography industry to check structural integrity, such as in pipeline welds. Americium-241-Beryllium neutron sources and Cesium-137 gamma-ray sources are used in the well-logging industry. Large curie teletherapy sources such as Cobalt-60 are used for cancer treatment. Other large sources of Cobalt-60 or Cesium-137 are employed in waste sterilization operations. Certain smaller sources are used in gauges or smoke detectors. Also covered in this study are shipments in urban areas of the Special Nuclear Material (SNM), such as Plutonium, Uranium-235, or Uranium-233, used as nuclear reactor fuels. These radioactive materials are shipped in packages which range in size from small, lightly shielded boxes containing radiopharmaceuticals, to casks weighing 25-100 tons containing irradiated (spent) fuel from nuclear reactors.

1.1.4 Related Studies

Several studies were performed in recent years which act as foundations or relate to this investigation.

WASH-1238[8] addresses the shipment of fresh fuel, spent fuel and waste associated with the operation of light-water reactors. It treats shipment by truck and rail, and estimates the effects along the route of transportation to and from reactor sites.

NUREG-0073[9] reports the results of a survey conducted by Battelle Northwest Laboratories on quantities and types of shipments of radioactive material transported in the U.S. between March 1, 1974 and February 28, 1975. In this investigation, questionnaires were sent to about 2300 of the approximately 18,000 licensees. Detailed questionnaires were mailed to SNM licensees who shipped 1 gram or more of material and to 150 "major shippers." This information was subsequently used to develop a data base on the types and numbers of radioactive material shipments in the United States. This data base provided important information for subsequent Sandia studies on transportation of radioactive material.

The present assessment follows NUREG-0170, a study performed by Sandia Laboratories to assess the environmental impacts resulting from transportation throughout the United States. That study estimates that "normal" or accident-free transport produces no short-term deaths, but on a statistical basis induces 1.2 latent cancer fatalities per shipment year as compared to the existing rate of 300,000 cancer fatalities per year. Transportation accidents were estimated to produce only one latent cancer fatality in two hundred years of shipping under 1975 conditions and rates. In spite of this low risk, specific accidents occurring in high population zones were found to have the potential to produce significant consequences--as many as 150 latent cancer fatalities and more than 100 million dollars in decontamination costs. The results in NUREG-0170 indicated that the urban environment is a significant factor in contributions to the risk. The unknown effects of the details of the urban environment on these estimates provided impetus toward another study to specifically analyze transportation impacts in an urban setting. The present report represents a significant milestone in that investigation.

1.2 Approach

The general approach developed in this study to assess both radiological and nonradiological impacts involved participation by the previously-mentioned task group. This task group assisted in the investigation by providing comments, suggestions, and advice on the scope of the work, the data base, and the important sub-programs and key tasks developed in the assessment.

The approach to radiological impact assessment primarily involved the development of computer models which quantify radiological environmental impacts resulting from transport of radioactive materials in urban environs using dynamic simulation techniques. A representation of the environment was developed whereby an urban area was divided into basic geographical units or cells, which were characterized by those parameters affecting the analysis. A specific section of New York City was analyzed to facilitate the application of the computer models and to provide a generic urban basis for the interpretation of the results.

Although some estimates could be made of the expected number of injuries and deaths resulting from transport of radioactive materials in urban areas on exclusive-use vehicles and certain other environmental impacts derived from the chemical toxicities of the various cargoes, a more qualitative approach has been used to assess nonradiological aspects such as previously observed or presently perceived social impacts.[10] Expected social impacts were assessed by review of the recent literature and application of the pertinent information by sociologists to develop key scenarios involving prospective social consequences of radioactive material transport through urban areas.[10]

1.2.1 Use of the Task Group

The Task Group on Transportation of Radioactive Materials in Urban Environs was formed early in this study to act both as an auxiliary source of information and as an informal review group.

The task group is ad hoc in that it functions for a period early in the investigation when a mechanism for external technical review and public comment is usually not available. It ceases to provide this unique function after public release of the First Draft Assessment, when the conventional review procedures involved in the preparation of an environmental impact statement become effective. The early delineation of the scope of the study, and the subsequent development of the technical programs were, therefore, intermingled with the functioning of the task group and the various ways it was employed to make the analysis more realistic and comprehensive. Input from the task group was facilitated through large public meetings, personal conversations, small meetings on special aspects of the study, and a limited number of written comments or statements on the work.

The four public meetings of the task group held rior to release of the Working Draft Assessment have provided opportunities for comments and recommendations to be made on the work by members of the task group as well as by attendees from the general public. The approach used by Sandia at these public meetings was to report the general status of the project, to review in detail the key programs being used in the analysis, and to schedule special opportunities for exchange of information among Sandia staff, task group members and other attendees. These special opportunities included a panel discussion and talks by guests or task group members in areas of expertise or interest.

Certain task group members have also given special guidance to the social impacts study and to other facets of the Working Draft Assessment at small meetings between the concerned parties. Individual task group members also provided comments and data by telephone or by written submissions. The minutes of task group meetings and other verbal or written statements connected with this study have been placed in the Public Document Room. The docket number for these records is PR-71,73 (40FR23768).

1.2.2 Approach to Radiological Impact Assessment

An approach was used to calculate radiological impacts which allowed consideration of those special features of urban areas which were thought to affect the doses received by surrounding populations. These urban-specific features, which include the shielding by buildings, the high traffic flow, and the presence of pedestrians, may produce different effects on the radiological impacts depending on the location of the shipment in the city and the time of day. These potentially variable factors were assessed through use of a grid composed of cells of specified geographic extent. Each cell was characterized by location and time: appropriate values for the parameters affecting the radiological impact analysis. A 100-square kilometer region in New York City was chosen for the detailed calculations.

A complex, radiological consequence model was originated which allowed quantification of those environmental impacts resulting from vehicular accidents, sabotage, human errors, and accident-free transport of radioactive materials in urban areas. For situations in which radioactive material may be dispersed, meteorological dispersion models were developed to predict the transport of radioactive material in street canyons and throughout the urban-regional area. Radiological consequences were quantified in terms of human health effects and decontamination costs.

1.2.2.1 The Urban Environment

The representation chosen to facilitate analysis of the radiological impacts on urban areas is illustrated by Figure 1 for a four cell grid. The cells in the grid represent specific geographical areas within a city. This approach allowed assignment of cell parameters to designate day-night population densities, traffic counts, pedestrian densities, building types, and other information characteristic of a given area. Such a grid also allowed specification of route and time of transport. Eight different directions were allowed for movement from cell center to adjacent cell center. As illustrated in Figure 1, time of transport was designated by referral to the daytime, nighttime, rush hour or "special" time spans assigned to the cell parameters.

A 100-square kilometer region in the Manhattan, Queens, and Brooklyn boroughs of New York City was used in the detailed analysis. The 400-cell grid, 10 x 10 x 4 and cartesian in three directions, is illustrated in Figure 2. This grid was selected to cover the maximum possible amount of land area with as much variation of land use as possible within computational constraints. As indicated by the projection in Figure 2, each cell extends 30 meters in the vertical direction.

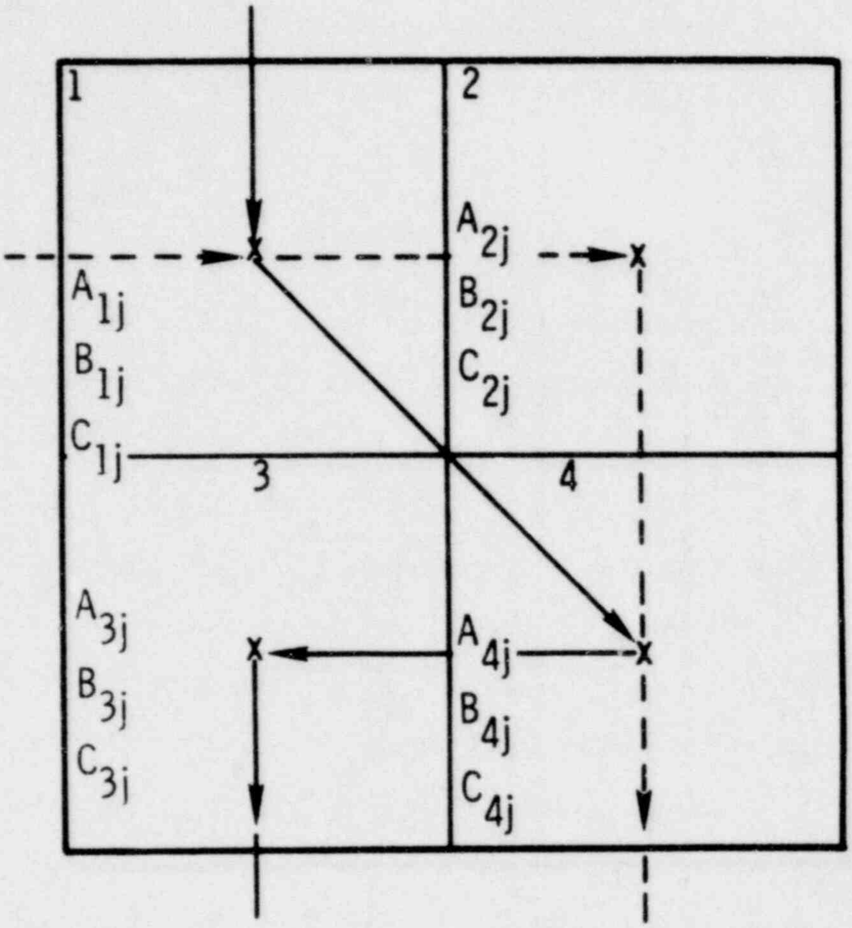

Figure 1. Four-Cell Grid

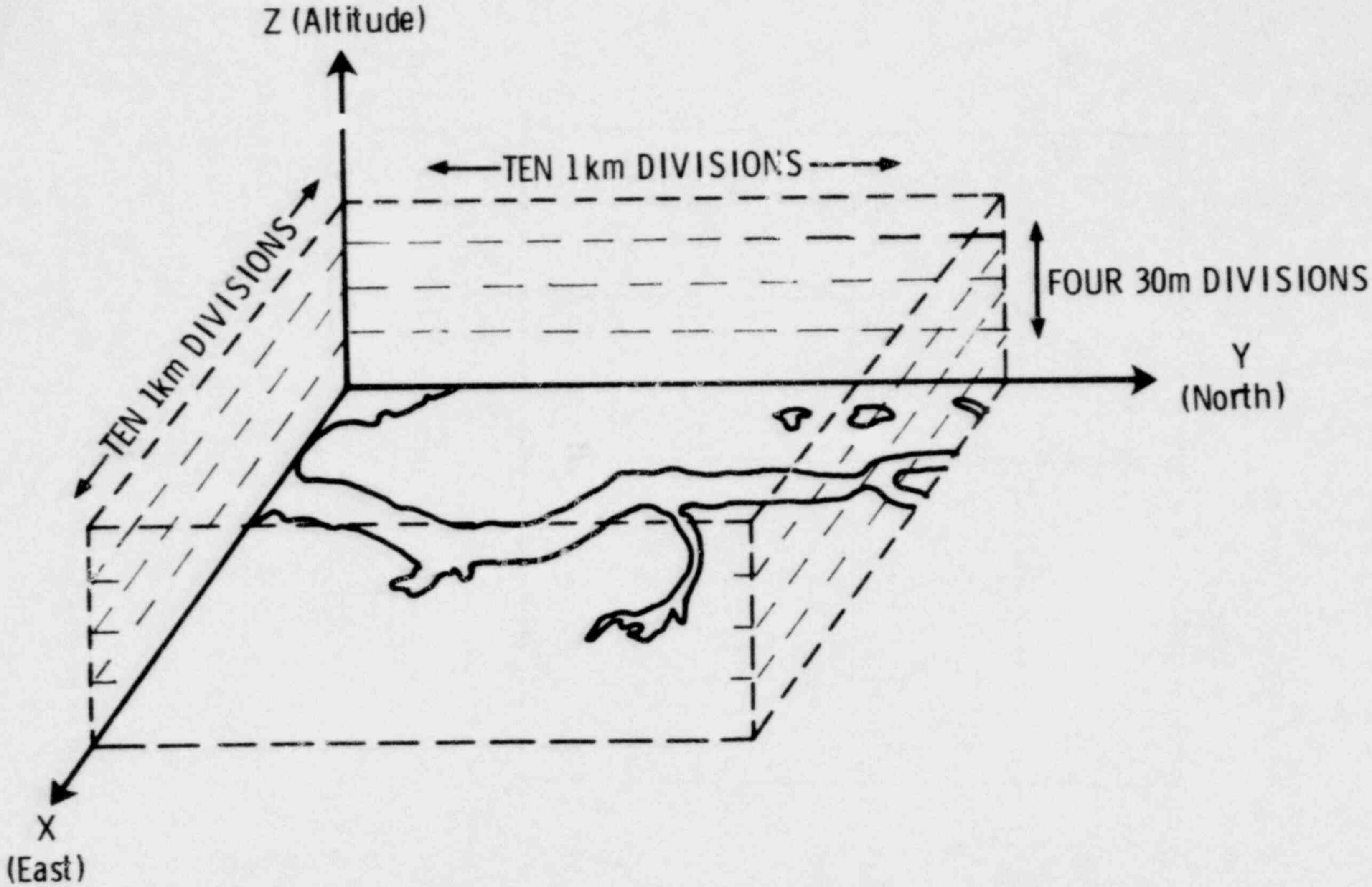

Figure 2. 400-Cell Grid

There are 11 cell dependent parameters used in the calculations; an example is the fraction of cell area covered by streets. There are 12 time-span-dependent parameters, e.g., the average speed of traffic on a freeway within a city. There are 7 cell-dependent and time-span-dependent parameters, e.g., the number of shoppers or "transient clientele." In addition, 26 grid independent parameters, such as vehicle separation distance at stops, are used in the analysis. These parameters and other input data used in the calculational approach for the grid representation of the urban environment are described in detail in Appendix A - The Urban Area Data Base. The routes through the grid, as specified by the sequence of the cells traversed and the time the grid is entered, are also discussed in Appendix A.

1.2.2.2 Radiological Consequences Computational Method

The general computer program structure used to calculate radiological consequences and risk is illustrated in Figure 3. The executive program, METRAN, quantifies radiological environmental impacts as a function of certain input data. These input data include those denoting the urban area characteristics, those delineating routes followed by radioactive material shipments and those describing the radiological sources, the packaging, and the transporting vehicles. METRAN estimates human health effects, such as expected latent cancer fatalities, and expected numbers of genetic effects produced by both accident-free transport and situations involving potential release of radioactive material.

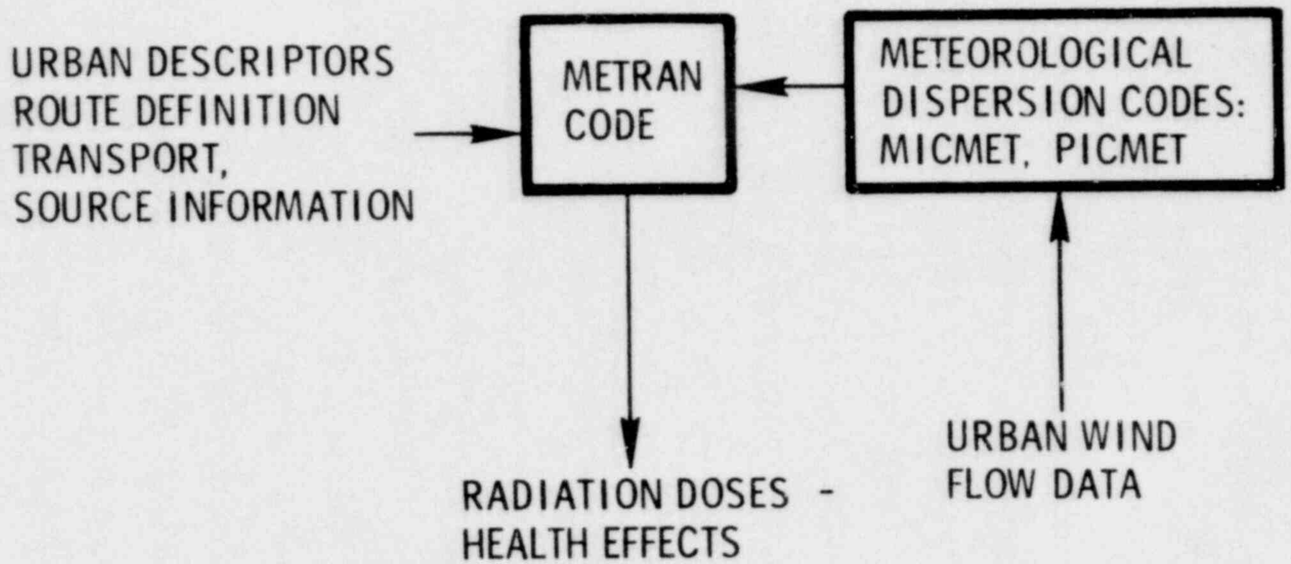

Figure 3. Radiological Consequences Method

In the case of accidents or sabotage, METRAN also receives input information in terms of volumetric and surface concentrations of the dispersed material as predicted by the meteorological dispersion codes: MICMET and PICMET. MICMET is a micrometeorological dispersion model developed to treat some of the features of air flows likely to be encountered in urban street canyons and at street intersections. The model is used both to estimate dispersion to the environment shortly after the release, and to provide initial conditions for the urban-regional transport model, PICMET, which follows the concentrations of radioactive material for longer distances and later times. In the PICMET model, the mean wind field is constructed from the available measurements of the horizontal mean wind field, the mean building height, and the fraction of open area pertaining to the lowermost cells in the grid.

1.2.2.3 Radiological Impacts

The approach to assessment of the radiological impacts involved development of certain dosimetric models. These are illustrated in Figure 4 for the accident and accident-free cases.

In the accident-free case, the dose rate from a point source of ionizing radiation was integrated over distance and time to deduce exposure to several surrounding population groups including crewmen, pedestrians, people in vehicles, people in buildings, handlers, and warehousemen. Subdivision of the population at risk in this manner allowed the inclusion of unique radiation exposure geometries and shielding considerations for each subgroup.

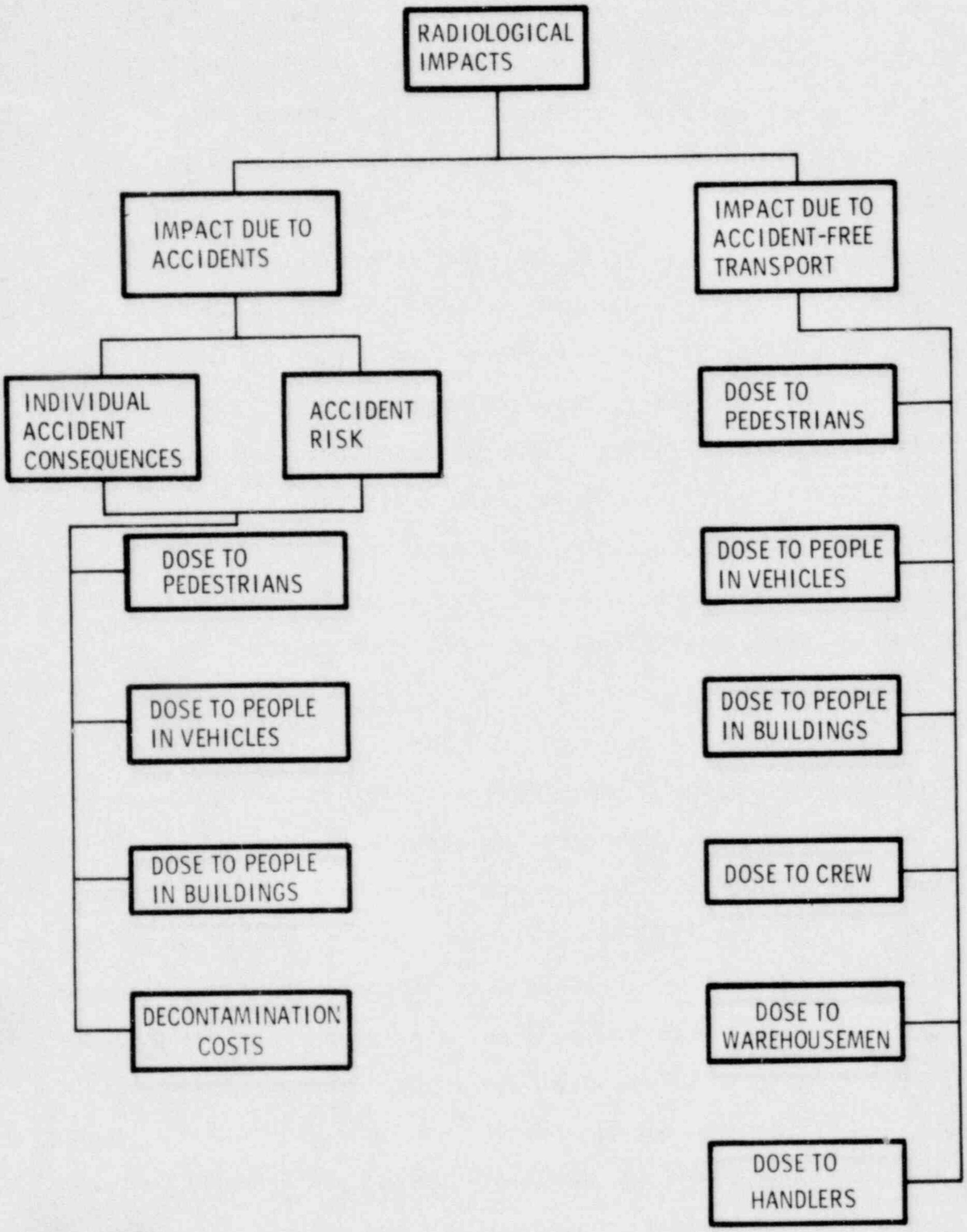

Figure 4. Dosimetric Models

Although the environmental impact of accidents may not be severe from an annual risk perspective, individual vehicular accidents during the transport of radioactive materials in urban areas have the potential for causing large health and economic consequences. Transported radioactive material was characterized as being either dispersible or nondispersible under accident conditions. Non-dispersible material was treated in a similar manner to that used to analyze accident-free transportation. Dispersible materials were assumed to be primarily an inhalation hazard. However, the dose from the passing cloud of released radioactive material and the dose from non-aerosolized material which remains at the scene of the accident were also explicitly included. The risk (probability of an event multiplied by the consequences of the event) was computed using vehicular accident rates and corresponding release fractions adapted from NUREG-0170.

The contribution to the risk from human errors was assessed using an approach similar to that used for vehicular accidents. The probability term, however, was computed using estimated error rates per package shipped correlated by radioactive material package type.

The radiological impacts from sabotage were also computed using the urban accident consequence model with appropriate modification in the source terms considered.

1.2.3 Approach to Nonradiological Impact Assessment

The approaches used to assess certain of the nonradiological impacts such as social impacts, usually involved less quantitative techniques than those employed to assess radiological effects.

This more qualitative approach was in part necessitated by the origin of certain social and socio-economic impacts in the perception and prospective behavior of individuals and groups. Social impacts are usually not displayed by empirical effects as with physical radiation damage but by individually-felt but socially-expressed fears concerning radiation hazards. These fears may be manifested in a different manner and, therefore, may produce different nonradiological impacts in an urban environment.

The personnel at the University of Texas Health Science Center at Houston School of Public Health and at Rice University, who performed the social impact assessment under contract to Sandia, used a literature research approach.[10] They reviewed and integrated existing literature concerning potential social impacts of transportation of radioactive materials. Informed sociological speculation was used to develop possible scenarios that would plausibly follow accident-free transport, vehicular accidents, and the sabotage of in-transit radioactive materials in urban areas.

Additional nonradiological impacts such as the effects of chemical toxicity of the transported materials and the impacts produced by transport on exclusive-use vehicles were also assessed. Health effects owing to chemically toxic materials resulting from inhalation or percutaneous adsorption of quantities of released material were estimated. The results of NUREG-0170 of the estimated number of nonradiological deaths and injuries attributable to radioactive material shipments on exclusive-use vehicles were extrapolated to the urban environment under consideration.

1.3 Summary of the Results

Radiological impacts of transportation of radioactive material in urban areas were found to be small: a total of ~ 800 person-rem was found to be attributable to the annual, accident-free transport of radioactive material through the New York City study area. This result is equivalent to ~ .02 latent cancer fatalities (LCF's). Overall risk attributable to vehicular accidents was found to be .003 LCF's, .007 genetic effects, .0007 early morbidities, and .00002 early fatalities for the shipment year. A risk of ~ .02 LCF's for the shipment year was found for certain conditions resulting from human errors or deviations from quality assurance practices.

Although serious accidents are unlikely, decontamination and evacuation costs, and income loss could amount to $[illegible] million following a major accident involving certain large shipments. Certain social impacts such as movements to restrict routes in urban environs could be expected to increase rapidly in the aftermath of such an event.

1.4 Contents of this Document

The subsequent chapters and extensive appendices of this report present the details of the investigation and the results obtained in the assessment of impacts of transporting radioactive materials in urban areas.

Chapter 2 and Appendices B and C describe the membership, operation, and contributions of the task group.

Chapters 3 through 7 report the analyses and the results of the principal environmental impact subject areas considered. Chapter 3 describes accident-free transportation in an urban environment.

The associated Appendix D details the accident-free dose model with an addendum describing certain of the mathematical approximations made in the computations. Chapter 4 reports the analysis made and the results obtained for the environmental impacts resulting from vehicular accidents in urban areas. The associated Appendix E details the dosimetric models employed in that analysis. Appendices F and G describe MICMET and PICMET, the micrometeorological and urban-regional models employed to predict transport of released radioactive material away from an accident site. Appendix H summarizes the radiological health effects model employed. Chapter 5 describes those impacts resulting from human errors or deviations from quality assurance deduced, in part, from the incident reports obtained from the DOT and the NRC as summarized in Appendices I and J, respectively. Chapter 6 describes the possible radiological consequences from sabotage of spent fuel casks and of other radioactive materials shipped in urban environs as well as the influence of the urban environment on present safeguards. Chapter 7 reports nonradiological effects such as impacts of chemical toxicity, and the additional impact on the environment of exclusive-use transport of radioactive materials.*

Chapter 8 discusses the effects of alternatives to present transportation of radioactive materials in urban areas such as changes in the transport modes employed or the routes followed.

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*The social impact study performed by personnel at the University of Texas Health Science Center at Houston and at Rice University is contained in a separate report.

Chapter 9 describes the sensitivity and error analysis performed to ascertain the key parameters affecting the results. The results of this analysis are used to consider the estimated impacts in a manner that makes them generally applicable to urban areas.

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CHAPTER 2

TASK GROUP

2.1 Introduction

2.1.1 Purpose

Environmental impact assessments involve the prediction, evaluation, and public discussion of the direct and indirect effects that policies and programs have on the social and natural environment. The goal of an impact assessment is to provide information for making decisions which minimize harm to biological and human communities, yet maximize the fulfillment of the wide range of needs of various public and interest groups.

Opening the process of impact assessment to public participation at an early stage is one way to assure that the information contained is complete and comprehensive. For this purpose, Sandia Laboratories formed a task group to provide a vehicle for limited public involvement in the impact assessment during the early stage of its development.

The use of such a group in this manner is not novel: as part of the State's Transportation Action Plan in Massachusetts, the Department of Transportation and Construction (and other signatories of the Metropolitan Planning Organization) have formed task groups of citizens, agency personnel, and special interest groups to participate in the preparation of environmental impact statements for major transit projects.[1]

2.1.2 Membership

The task group organized to provide public participation in this impact assessment is composed of individuals who are affiliated with federal, state, and local government agencies as well as persons involved in industry, public interest groups, and universities. The twenty members of the task group, as well as designated alternates, are listed in Appendix B.

Task group members include experts in the area of transportation of radioactive materials and related fields, sociologists, officials in the New York City area, residents of adjoining states, and people experienced with the activities of citizen groups.

The members were requested to express their opinions rather than act as official spokesmen. No consensus was expected on the various issues to be explored during the meetings or during other operations of the task group.

2.1.3 Operating Procedures

The operations of the Task Group on Transportation of Radioactive Materials in Urban Environs were administered by Sandia staff using the procedures described in Appendix C. These operations included arranging, advertising, and conducting the task group meetings. When required, task group members were compensated by Sandia for travel expenses and time spent away from regular employment. The task group was kept informed of developments affecting the schedule, technical progress, and review of the work. Statements made by members were distributed by Sandia to the task group upon request, and also placed in the Public Document Room. The docket number for these records is PR-71,73 (40FR23768).

Sandia assumes full responsibility for the results of this study. Because of this responsibility, Sandia staff exercised judgments in the acceptance of ideas from the task group. This means that not all advice and recommendations supplied by the various task group members were used in the development of the impact assessment.

2.1.4 Public Meetings

Four public meetings of the task group have been held. One meeting is planned after issuance of the Working Draft Assessment. These meetings were held with major consideration given to the convenience of the majority of task group members. Some attention was given to geographical locations to promote public attendance and involvement of interested local officials. The group met at large hotels which could provide adequate facilities.

The public meetings were designed to provide for an open exchange of ideas and information. Usually this involved a briefing by members of the Sandia staff, followed by question and answer periods. Less frequently, talks were given by task group members on areas of particular interest or expertise. A Sandia employee usually acted as moderator for the sessions. The agenda for the usual two-day meeting provided a period for audience participation; at one meeting a panel discussion was held involving prominent residents; at another meeting the Task Group toured port facilities and was briefed by transporters of radioactive materials.

Minutes were taken at the public meetings. The draft version of these minutes was mailed to the task group and the attendees noted on the sign-in sheets. After revision, the meeting minutes were placed in the Public Document Room.

2.2 Task Group Meetings

2.2.1 First Task Group Meeting: New York City

The first meeting of the Task Group on Transportation of Radioactive Materials in Urban Environs was held September 20, 1976 at the Warwick Hotel in New York City. Its purpose was to outline the investigation to the task group, explain the approach, and receive initial suggestions on the developing study.

After a presentation of Sandia's preliminary technical approach to the impact assessment, the meeting was opened to discussion by the Task Group and visitors from the public. Although a broad spectrum of opinion was expressed by the participants, a number of issues received special attention. Several members of the task group pressed for an expanded treatment of nonquantitative areas involving potential sociological and psychological effects of transport of radioactive materials in urban areas. Other areas of major concern related to sabotage possibilities, military shipments of radioactive material, and the jurisdictional questions involved in the general area of accident response.

This organizational meeting also included discussion of task group procedural matters such as the number and location of meetings and discussion of ways to expedite exchange of information between the Task Group and Sandia personnel. Many of the task group members could provide information on transportation of radioactive materials in urban areas and also act as sources for important data needed in the model description of the New York City study region. Some task group members suggested that Sandia personnel provide briefings on key technical areas involving related work on packaging of radioactive material.

2.2.2 Second Task Grcup Meeting: Arlington, Virginia

The second task group meeting was held November 16 and 17 at the Quality Inn - Pentagon City in Arlington, Virginia.

The first day was devoted to presentations by Sandia personnel describing related Sandia transportation projects and the status of the urban study. NUREG-0034,[2] the recently completed Sandia study to assess the radiological and nonradiological impacts of radioactive material shipments throughout the United States, was reviewed. Although the radiological impacts were estimated to be small in that study, the largest component of that impact was reported to involve transport under "normal" or accident-free conditions. Various transport alternatives of interest to the task group, including shipment of certain radioactive materials by barge, were also discussed.

Packaging studies underway at Sandia were described for the task group. Procedures covering fire, drop, crash and immersion tests were explained. Many task group members were particularly interested in the testing of packages used to transport plutonium such as the 6M and the PAT (Plutonium Air-Transportable) containers.

The ERDA film <u>On the Move</u>, which describes packaging procedures and safeguards involved in shipping radioactive materials, was shown as part of the briefing.

Also included was a status report on the urban study. The subjects covered included social impacts, the geographic extent of the model, accident response, sabotage and diversion, yellow-cake shipments, and the prospective format of the study results. Questions from the task group mainly addressed the consideration of possible sabotage scenarios and the geographic extent of the model to be used in the urban analysis.

The second day of the meeting featured discussion of the key subject areas of social impacts, accident scenarios in New York City, and accident response. Task group members acted as discussion leaders.

Sources of information, methodologies for decision making, and social questions affecting responsibility, regulation, and transport were developed in the social impact discussion. Public perception of the risk, the development of political groups, and social acceptance in general were major aspects of this discussion.

Special attention was focused by some members of the task group on the shipment of spent fuel and plutonium through the "hyper-urban" environment offered by certain portions of New York City. The possibility of severe accidents involving air transport of plutonium were suggested as well as large consequences from terrorist activities or unforeseen events. Some members thought other large shipments of radioactive material such as Cobalt-60 should be analyzed. Others argued that any hazard represented by such shipments would be transferred to the citizens of states adjoining New York City if routing were altered to minimize transit of urban areas.

The discussion of accident response included aspects of accident prevention and jurisdictional questions. Present emergency plans were considered including notification and response procedures. Other important questions developed during this meeting related to the areas of quality assurance, health effects, and international shipments of radioactive materials through American ports.

2.2.3 Third Task Group Meeting: Baltimore, Maryland

The third meeting of the task group was held March 29 and 30, 1977, in the Holiday Inn, Baltimore.

The first day of this meeting featured a review of the technical programs being developed at Sandia to perform the environmental impact assessment. After an overview of the project status, presentations were made on the radiological consequence model, the meteorological dispersion model, and the recently initiated quality assurance study. Questions and suggestions were received from the task group and members of the public who contributed to the discussion.

The study area, special features of the assessment and the general program structure were explained in the overview. A review was given of the membership, the purpose and the operating schedule for the task group, as well as the subjects emphasized at earlier task group meetings. Also explained were the types of urban data being sought for the analysis. Available shipment information was provided by listings of radioactive material shipments through Baltimore in 1975 from the data base management of Battelle survey information.[3]

Discussion of the radiological consequence model, METRAN, included radiological health effects, the characterization of the urban area, elucidation of the dosimetric sub-models, and description of both accident and accident-free transport sequences. The question and answer session dealt primarily with such topics as exposure pathways, population groups considered, accident severities, and expected release fractions. Several task group members suggested broader treatment, and cautioned Sandia against narrowing the focus of the study or becoming constrained by the modeling.

The methodology under development for the meteorological dispersion models to be used for description of release of radioactive material in urban areas was also reviewed. The status of the micrometeorological (small-scale) transport model and PICMET (urban-regional model) was reported. The actual wind-field data available for New York City were also discussed. Questions related to wind flow patterns expected in an urban environment.

A briefing was given on the quality assurance investigation recently undertaken in connection with the urban study. A preliminary approach was outlined involving acquisition from federal, state, and commercial sources of data required to estimate human error rates. Certain task group members suggested that deviations from quality assurance and other human errors may occur which are not revealed in the incident reports.

Before the close of the first day of the meeting, a representative of the American College of Nuclear Physicians offered the group's cooperation in assessing impacts involving radiopharmaceuticals.

The morning session of the second day involved briefings on safeguarding of radioactive material given by staff personnel from the Nuclear Regulatory Commission. In addition, a discussion of potential civil liberties questions was conducted by a task group member.

A review was given of NUREG-0194[4] involving calculations of radiological consequences estimated from sabotage of casks containing spent fuel or high level waste. These calculations were stated to involve maximum sized casks and a uniform population density of 100 people/mi^2. The consequence model used in WASH-1400[5] involving many weather histories and a central estimate model for health effects was applied to several assumed release fractions. On the basis of these calculations, the number of expected deaths in the surrounding population was asserted to be small.

Certain task group members took exception to the conclusions of NUREG-0194, particularly those for urban areas. The population densities were admitted to be too small for the analysis of an urban area. Some members predicted large consequences in the event of sabotage of large spent fuel casks during transport through a city.

Present security and safeguards for shipment of certain radioactive material were also elaborated. It was stated that present safeguards require physical protection to be applied to licensees who ship 5 kilograms of uranium-235 (contained in uranium enriched to 20 percent or more), two kilograms of plutonium or uranium-233 or a weighted combination of these.[6] It was pointed out that current safeguards do not extend to the transport of spent fuel or high level waste.

Certain members of the task group expressed interest in what problems might be involved in safeguarding shipments of radioactive materials through urban areas. The question of the extra costs to private companies of regulations which require additional safeguards was also raised.

One task group member discussed the civil liberties questions which might arise in the protection of citizenry from sabotage or terrorist activities. These included the potential use by authorities of lie detector and background tests. An opposing opinion expressed the view that people who volunteer information, such as those obtaining security clearances, do not have their liberties restricted.

During the second day of the meeting, a tour was made by the task group of the Port of Baltimore facilities used to ship radioactive materials. The briefing given at the Dundalk Terminal in connection with this tour revealed that many diverse radioactive materials are being shipped involving traffic managers, truckers, railroads, container companies, and freight forwarders. Controls exercised by the Maryland Port Authority and the U.S. Coast Guard were also explained.

The shippers at the briefing contended that radioactive materials are treated like any other hazardous commodity. Questions from the task group addressed areas such as training of responsible personnel and readiness to respond to accidents or similar emergencies involving radioactive material.

2.2.4 Fourth Task Group Meeting: Houston, Texas

The fourth meeting of the Task Group on Transportation of Radioative Materials in Urban Environs was held July 13 and 14 at the Brookhollow Hilton Inn, Houston, Texas.

The first day of this meeting involved review of the key programs in the assessment by Sandia personnel, general discussion of the interim report, and transmittal to Sandia of written comments on the interim report prepared by members of the staffs of the Environmental Protection Agency and the Nuclear Regulatory Commission. A special evening session featured a panel discussion on transportation of radioactive materials in urban areas.

A status report was given on the urban study covering the history, the scope, recent progress, the schedule, and new subject areas incorporated in the investigation. As stated in this overview, Houston was chosen for the meeting because of the assistance offered by the local people and its importance as a large urban area through which considerable quantities of radioactive material are shipped.

The review of the sub-programs of the assessment examined the major changes which have occurred since the issuance of the interim report in the radiological consequences and meteorological dispersion models as well as in the quality assurance study. An update was given on the data base which has been assembled to provide needed description of the New York City area and to furnish other required inputs to the study.

As reported, the model to assess the radiological impacts from truck transport of radioactive material has been expanded to treat other models of transport. In addition, improvements in the methods used to calculate dose to people in buildings and dose to people in vehicles were discussed. Cloudshine dose (exposure from a passing cloud of radioactive material) was reported to be recently included in the model. Early morbidities were stated to be recently incorporated in the health effects considered under radiological impacts. The concept of "remnant dose," now used to account for effects owing to radioactive material left at an accident scene, was also described. Questions from the task group related to neglect in the model of the ingestion pathway and the present consideration of accident response via calculation of an accident delay time.

Progress and improvements noted in the meteorological dispersion models included the determination of a set of typical and atypical wind flow patterns, corrections to the vertical mean wind, and computations of the particle envelopes as a function of dispersed time. Task group members were most interested in what constituted worst-case weather conditions and how variant weather conditions would be considered in the analysis.

The review of the quality assurance investigation revealed that additional data sources had been located since the completion of the interim report. Sources included reports from the agreement states, the Department of Transportation, the Canadian government, and private companies. The task group and the audience suggested that accident reports should still be sought from the individual states, and that data on spent-fuel shipments should be extracted, if possible, from all available sources of information.

The data base discussion detailed categories of information being obtained for the 100 cell grid under specific study in the Manhattan-Queens-Brooklyn area of New York City. These included demographic data, land-use information, building characteristics, and traffic, shipment, and accident data. Dosimetric parameters were also stated to be a key requirement of the analysis of radiological impacts owing to transport of radioactive materials in urban areas. Questions concerned the information obtained from the Battelle survey[3] and existing traffic and route restrictions for New York City. Corrections to the data, such as characteristics of buildings in New York City, were offered by members of the task group.

Written comments from members of the staffs of the EPA and the NRC on the interim report were submitted to Sandia. These were not official comments of those agencies but represented individual staff member opinions offered as early input to the urban study. In general, these comments addressed the preliminary assessment methodology and models described in that report. Salient EPA staff comments discussed at the meeting involved corrections to the building characteristics and to the ventilation intakes assumed in the interim report.

Detailed NRC staff comments were also presented at the meeting. These comments addressed the data base, health effects, dose calculation, transport models, the quality assurance study, and the general scope of the work contained in the interim report.

In response to these comments, the Sandia staff explained that an error analysis was underway to provide the generic basis of the assessment. A sophisticated meteorological dispersion model was used because simpler models could not reasonably treat the release environment required in this study. Some parameters were used in the interim report in lieu of better data. Many parameters were recently changed to reflect improved knowledge. In view of the comments, areas such as the estimation of thyroid cancers and the treatment of backscattering from buildings to pedestrians would be given further study.

An evening panel discussion was held involving eight members. Each panel member made a brief opening statement prior to general debate of the issues. Time was also provided for discussion of the questions of special interest to those attending.

The opening statements of the panelists reviewed several areas of individual concern. These included future transport of radioactive waste, compensation for any injuries or damage sustained because of transport of radioactive material; the freeway dependence of a large segment of present transport in and around large cities; possible jurisdictional questions in regulation and in accident response; possible cancer induction and other health effects from radiation exposure; and potential for nuclear blackmail. Opinions expressed by individual panelists were that labeling of radioactive material packaging should be improved; that people exposed to passing shipments should be notified of any exposure; that alternate transport modes might be used to avoid transport of radioactive material near population centers; that present transport of radioactive materials is very safe and that regulation and response capabilities are adequate; that social impacts are very important; and that early suggestions by the public concerning regulation and legislation are desirable.

The open discussion expanded many of the issues raised by the panelists in their opening statements. Other interesting aspects raised concerned local route restrictions on transportation of radioactive material, public fear of radioactivity as compared to other hazardous cargo, decontamination costs in the event of release in an urban area, and local viewpoints on environmental questions and on federal preemption of state or local authority.

The second day of the meeting involved an elaboration on some of the issues developed at the panel discussion, and briefings on the sensitivity/error analysis, social impacts, and urban safeguards portions of the assessment.

The current embargo on the passenger aircraft transport of radioactive materials not used for either medical or research purposes was one major topic of discussion. Other important topics related to the training programs for local and state personnel concerned with response to accidents involving transport of radioactive materials.

The briefing on the sensitivity/error analysis revealed two primary objectives of that study: (1) to identify the parameters of the transportation system which determine the level of public safety; and (2) to determine the range of uncertainty in the calculated environmental impacts owing to natural variations in these parameters. One method explained for accomplishing these objectives was that of response surfaces. Peaks in the response surface were described as indicative of regions of high variable sensitivity. Members of the task group sought additional information on how errors would be displayed in the report and how they might be interpreted for meaningful decision-making.

The briefing on the urban safeguards study explained two aspects of that investigation: the first, to analyze the consequences of sabotage of shipments which are not currently protected; the second, to investigate the incremental effect on safeguarded shipments of the urban setting such as changes in police response time. The task group expressed interest in whether hijacking or other diversion of radioactive material would be covered in the urban safeguards study. It was explained that this would be investigated, but no information of potential use to terrorists would be publicly released.

The objectives set forth for the social impacts study included a review and synthesis of existing literature, identification of key transportation scenarios, and the elucidation of expected social impacts. The social impacts identified involve collective behavior, such as political movements, as well as individually-felt but socially expressed fears concerning radiation hazards. It was stated that the social impacts aspect would be integrated into the general framework of the study to encompass impacts owing to accident-free transport as well as those related to accidents and sabotage. The subsequent discussion of social impacts with the task group addressed topics such as communication, public awareness, civil liberties, crowd behavior, nuclear versus nonnuclear shipments, attitudes of people involved in transport of radioactive materials, and the actions and responsibilities of public officials.*

2.2.5 Meetings on the Social Impacts Study

Two meetings involving limited task group participation were held to review progress on the social impacts study being performed under contract to Sandia by personnel at the University of Texas School of Public Health and Rice University. Task group members Ida Hoos and Richard Pollock, who are experts in this area, assisted Sandia personnel in this review by their comments and suggestions. The NRC task leader, Norman Eisenberg, was also invited by Sandia to attend these discussions.

*Detailed discussion of social impacts is being published separately.

The first meeting was held on September 1, 1977 in Houston, Texas. The progress report on the study stated that other situations besides disasters were being analyzed to ascertain representative social impacts. Possible scenarios were being developed for transportation of radioactive material in urban areas along with corresponding social impact severity indices. Those attending commented on what scenarios might be representative. Information was given to the Houston group on package types and shipment sizes. It was recommended that the research be directed toward identification of the key parameters which can significantly influence the magnitude of the social impacts. It was also suggested that contact be maintained throughout the study with task group members and other experts in this area of transportation.

A second meeting was held January 5, 1978 in Albuquerque, New Mexico to review the draft of the social impacts study principally prepared by Professor Chad Gordon of Rice University. Comments on the draft were made relative to perceived omissions in the treatment of areas such as accident-free transport, non-fuel-cycle transport, and industry viewpoints. Several comments dealt with focus of the work toward transportation and away from reactor safety questions. It was further recommended that all statements made in the report be carefully documented by appropriate references. Sandia provided Dr. Gordon with information in the form of newspaper articles on social impacts resulting from the transport of spent-fuel through New York City and Connecticut.

2.3.1 Scope

The scope of the environmental assessment was substantially broadened by the comments, suggestions, and concerns expressed by the task group. This led to expansion of the investigation to encompass special and more detailed attention to such topics as social impacts, urban safeguards, and quality assurance.

Many points of discussion at the task group meetings were of a social and socio-economic nature involving questions which could not be answered by the models being developed by Sandia for quantitative risk assessment. Questions included: who receives the benefits and who incurs the costs of transportation of radioactive material; what are the social impacts of severe accidents, sabotage, or nuclear blackmail; how do people perceive the possible dangers and benefits of transport of radioactive material in urban areas; how do jurisdictional questions affect accident response; how do such parameters as public awareness, action of authorities and political groups affect social impacts related to transportation of radioactive material in an urban environment? These and other questions precipitated a request from Sandia to the NRC to expand the work in the social impact area.

Several people on the task group, especially those from the New York City area, expressed concern over the possible sabotage of large shipments of radioactive material being transported through and around large population centers. The review of previous safeguards studies showed that they are either inadequate or unadaptable to the urban safeguards questions that were being raised at the public meetings of the task group. The scope of the environmental assessment was again expanded to address this aspect. The study initiated by Sandia personnel with NRC support examined the consequences of sabotage of spent-fuel casks and other presently unprotected shipments as well as the effects of the urban environment on present safeguards.

Several members of the task group expressed concern over the impacts produced through human errors which are not covered in the study by the analysis of vehicular accidents. It is generally known that a large percentage of reported incidents relate to these human errors or deviations from quality assurance. The portion of the risk attributable to error, however, was not known. A study was initiated, therefore, to review the incident reports with the objectives of ascertaining error rates and estimating this contribution to the environmental impacts.

2.3.2 Technical Assistance

Task group members provided critiques of the Sandia technical models, gave information on important parameters used in the analysis, and suggested leads for data sources.

Several changes were made in the technical models as a result of review by the task group at the public meetings. These changes included modification in the building air intake assumptions, in the treatment of nonrelease accidents, in the health effects considered, and in the wind model used in the meteorological dispersion analyses. Model changes were sometimes not directly contributed by the task group but resulted from their questions and the subsequent consideration given these inquiries by the Sandia staff.

Considerable assistance was provided to Sandia by members of the task group in the location of data needed in the study, including: routing information on shipments of radioactive materials, characteristics of buildings in the New York City area, and radioactive material incident reports. In addition, several leads on data sources on water transport, incident files, and other areas were obtained from task group members.

2.3.3 Public Input

Public attendance reflected the large, diverse interests in the transportation of radioactive materials near and through urban areas. Many people who attended the meetings were affiliated with local industry, environmental groups, and governmental organizations. Their opinions largely reflected these special interests.

The panel discussion and other opportunities for public input demonstrated that questions and concerns about radioactivity and radioactive materials in general extend to the issue of transportation. The shipment of radioactive waste, prospective health effects, and government regulation seem to be major subjects of public interest.

REFERENCES

1. State Transportation Action Plan, State of Massachusetts.

2. U.S. Nuclear Regulatory Commission, Office of Standards Development, Draft Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes, Docket No. PR-71, 73 (40 FR 23768) NUREG-0034, March 1976.

3. U.S. Nuclear Regulatory Commission, Survey of Radioactive Material Shipments in the United States, BNWL-1972, April 1976.

4. U.S. Nuclear Regulatory Commission, Division of Safeguards, Calculations of Radiological Consequences from Sabotage of Shipping Casks for Spent-Fuel and High-Level Waste, NUREG-0194, February 1977.

5. Reactor Safety Study, An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants, WASH-1400, October 1975.

6. 10 CFR 73.

CHAPTER 3

RADIOLOGICAL IMPACTS FROM ACCIDENT-FREE TRANSPORT OF RADIOACTIVE MATERIALS IN URBAN AREAS

3.1 Introduction

Transportation of radioactive materials can result in environmental impacts even when no accidents or other abnormalities occur to compromise package integrity. These accident-free radiological impacts result from exposure of surrounding population to external penetrating radiation. A previous study[1] indicated that the radiological environmental impact from accident-free, or "normal," transport may be significantly greater on an annual risk basis than those impacts resulting from vehicular accidents. Although the consequences to individuals may be extremely small, overall population impacts from low dose, low dose-rate radiation can occur and may be significant because of the large number of radioactive material shipments which occur annually in the United States,[2] many involving transport in urban areas. These radiological impacts from accident-free transport of radioactive materials are considered in detail in this chapter.

A standard shipments model is used to describe the movement of radioactive material through the New York City grid, and to account for shipments which originate in or are destined for New York City. These shipments are standardized by end-use, transportation mode, and other aspects of routing. Through-shipments in a single transport vehicle, and transport from one vehicle or mode to another are considered to be within the study area.

The mathematical basis for the calculation of impacts from accident-free transport is the point-source approximation which uses typical package dimensions and the transport index--TI* to estimate the radiation level at various distances from that source. Integrated population exposures associated with each of the standard shipments are estimated by the model. Radiation doses to urban population groups, such as those received by pedestrians, by people in vehicles, and by people in buildings are considered in this analysis of radiological impacts from accident-free transport of radioactive materials.

When annual shipping rates are included, the annual radiological consequences from accident-free transport can be expressed in terms of annual expected person-rem. These impacts on urban population groups are analyzed with respect to transportation mode, package type, and end-use.

3.2 Standard Shipments Model

As detailed in Appendix A, approximately 300,000 shipments were ascertained to be transported into, out of, and through the New York City area during the reference shipment year. In order to make this large traffic tractable in terms of radiological impact assessment, a list of standard shipments was compiled as a function of end-use (medical, industrial, etc.). Each of the groups of end-use sets was assigned to one of 17 routes through the grid. This list of 17 routes is given in Table 1.

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*A measure of the radiation level external to a package-dose rate in mrem/hr. at 3 ft. from the surface of a package. This index is defined in 49 CFR 173.

TABLE 1

Standard Shipments Information by Route*

Route Number	End-Use	Mode
1	Medical	1°** - air freight 2°** - truck
2	Medical	Truck
3	Medical	Air freight overflight
4	Medical	Truck
5	Industrial	Truck
6	Industrial	Air passenger overflight
7	Industrial	1° - air freight 2° - truck
8	Industrial	Truck
9	Fuel Cycle	Ship
10	Industrial	1° - air passenger 2° - truck
11	Waste	Truck
12	Fuel Cycle	Truck
13	Medical	Air passenger overflight
14	Industrial	Air freight overflight
15	Medical	1° - air passenger 2° - truck
16	Waste	Truck
17	Fuel Cycle (spent fuel shipments)	Truck

*Further information on specific isotopes shipped by each route may be obtained from routing tables in Appendix A.

**1° indicates primary transport mode. 2° indicates secondary transport mode.

These routes were established for each standard shipment by transport mode. Specific routes through the grid are detailed in Appendix A.

Table 2 displays the standard shipments information by end-use: shipments having medical applications predominate in the number of annual shipments and with respect to TI per year. A smaller number of large curie shipments constitute fuel cycle and industrial uses. Waste shipments of low average curie content contribute only slightly to radioactive material transport in the urban area.

TABLE 2

Standard Shipments Information by End-Use

End-Use	Packages/ Year	Percent of Total	Curies/yr	Percent of Total	TI/year	Percent of Total
Medical	2.27×10^5	80.5	4.65×10^5	12.2	9.15×10^5	78.7
Industrial	3.10×10^4	11.0	7.20×10^5	19.0	1.26×10^5	16.0
Fuel Cycle	2.32×10^4	8.2	2.61×10^6	68.7	5.77×10^4	5.0
Waste	9.60×10^2	0.3	6.00×10^{-2}	-	4.58×10^3	0.4
Totals	2.82×10^5*		3.80×10^6		1.16×10^6	

*Does not include limited shipments.

Standard shipments information by mode is summarized in Table 3. The largest number of annual shipments of radioactive material and total TI involve truck transport. Shipments by air are next in importance; transport by ship accounts for a smaller percentage of the total annual shipments of radioactive material in the urban area.

TABLE 3

Standard Shipments Information by Mode

Shipment Mode	Packages/ year	Percent of Total	Curies/yr	Percent of Total	TI/year	Percent of Total
Truck	1.52×10^5	53.9	3.24×10^6	85.3	7.02×10^5	60.4
Air Freight	4.75×10^4	16.8	4.61×10^5	12.1	2.59×10^5	22.3
Air Passenger	5.95×10^4	21.1	9.80×10^4	2.6	1.44×10^5	12.4
Ship	2.31×10^4	8.2	4.85×10^1	-	5.75×10^4	4.9
Totals	2.82×10^5*		3.80×10^6		1.16×10^6	

*Does not include limited shipments.

Table 4 shows the summary of the standard shipment information by packaging: type A packaging accounts for the largest number of packages shipped and is the largest contributor to total annual TI. A smaller number of large casks and type B packages contribute more significantly to the total curies shipped in the New York City study area.

TABLE 4

Standard Shipments Information by Package Type

Package Type	Packages/ year	Percent of Total	Curies/yr	Percent of Total	TI/year	Percent of Total
A	2.54×10^5	87.5	2.60×10^5	6.8	1.04×10^6	89.2
B	2.68×10^4	9.2	6.43×10^5	16.9	1.22×10^5	10.5
Drum	7.60×10^2	0.3	2.82×10^5	7.4	4.37×10^3	0.4
Cask	1.20×10^1	-	2.61×10^6	68.7	--	-
Limited	8.63×10^3	3.0	5.50×10^1	-	2.10×10^2	-
Totals	2.91×10^5		3.80×10^6		1.16×10^6	

3.3 Dosimetric Models

Detailed dosimetric models were developed to facilitate assessment of the radiological impacts from accident-free transport of radioactive materials in urban areas. The actual formulae for the doses, described in Appendix D, were derived by manipulation of the expression for dose rate from a point source of ionizing radiation (Eq. D-1). The formulae combine the TI, a shape factor, attenuation, geometric dose reduction, and dose buildup. These dosimetric models allow estimation of integrated doses to the various population groups at risk along the transport routes.

3.3.1 Dosimetric Models for Accident-Free Truck Transport

The population exposed to doses from penetrating radiation during truck transport of radioactive materials was divided into six groups, which include population subsets which reflect special demographic aspects of an urban environment. These population groups are pedestrians, people in buildings, people in vehicles, handlers, crewmen and warehousemen. The dosimetric models include variations which allow consideration of truck transport of radioactive materials on two-way streets, one-way streets, and freeways.

3.3.1.1 Pedestrians

The dosimetric model for pedestrians assumes a truck shipment moving down the street at a constant speed with equal numbers of pedestrians walking in opposite directions on both sidewalks. Critical parameters affecting exposure include pedestrian density, the relative velocity of the vehicle and pedestrians, and the distance of closest approach. Besides the direct exposure from the truck shipment, the analysis of dose to pedestrians includes a component resulting from scattered radiation from the ground or from the surfaces of adjacent buildings.

3.3.1.2 People in Buildings

Computation of dose to people in buildings from penetrating radiation includes consideration of the shielding provided by intervening building material and of distances affecting exposure to people on upper floors. Buildings themselves are characterized by principal construction material, wall thickness, and building height. Buildup from secondary gamma emission in concrete and the effect of the oblique impingement geometry are also evaluated.

3.3.1.3 People in Vehicles

This dose model accounts for exposure to people in vehicles moving in the same direction as the shipment, and to persons in vehicles moving in the direction opposite to the shipment. No shielding is assumed to be provided by the vehicles themselves. Both a cruising phase and a stopped phase are considered for the shipment and the surrounding traffic. The bunching of vehicles at intersections is assumed in the latter case to compute total dose to people in vehicles sharing the transport link.

3.3.1.4 Crewmen

Crewmen aboard a vehicle transporting radioactive material are exposed to penetrating radiation for the duration of the shipment. This exposure is critically dependent on the total shipment TI, the source-to-crew distance, and the travel time.

3.3.1.5 Handlers

Dose to handlers, which can apply to any transport mode, is computed using information obtained from previous assessments of package handling.[3,4] For small packages of radioactive material, dose to handlers is a function of shipment TI, the number of handlings, and empirically derived information on person-rem/handling/TI. Handling or rigging of large packages or casks is not expected in urban areas.

3.3.1.6 Warehousemen

Packages stored during any part of the shipment cycle can result in accident-free dose to warehousemen. This dose is directly proportional to the shipment TI, the storage time, the number of warehousemen, and the exposure distances.

3.3.2 Dosimetric Models for Accident-Free Rail Transport

The dosimetric model for accident-free rail shipments considers exposure to penetrating radiation of people along the right-of-way and in rail terminals. Dose to persons sharing the transport link is also analyzed.

3.3.2.1 People in Rail Terminals

The population in a terminal area is assumed to be distributed in an annular area extending radially from a distance of closest approach to some maximum distance from a shipment of radioactive material. The integrated dose is a function of these distances as well as the average stop-time and population density in the depot area.

3.3.2.2 People Sharing the Transport Link

Passengers in trains which pass the shipment of radioactive material in the opposite direction are exposed to short-term, low-level radiation. This exposure depends on the train traffic count, the number of persons per train, the average train velocity, and the separation between passing trains.

3.3.2.3 Persons Along the Right-of-Way

The population groups adjoining railroad tracks are approximated by an average population density. The exposure to persons along the right-of-way is directly proportional to this population density and involves width of the right-of-way.

3.3.3 Dosimetric Model for Accident-Free Air Transport

Air shipment of radioactive materials can occur on passenger or cargo aircraft. A previous study[1] has evaluated the accident-free doses received by crewmen, flight attendants, and any on-board passengers. These doses are not appreciable during transit of an urban area. The dose to people in the air terminal, however, is pertinent to this study. That dose is similar in mathematical expression to the dose received in rail depots; i.e., it is dependent on the terminal population density, the average stop-time in air terminals, and the minimum and maximum radii assumed in the model for the annulus enclosing the exposed population.

3.3.4 Dosimetric Model for Accident-Free Waterborne Transport

Ships and barges carrying radioactive material expose people in urban areas to penetrating radiation when they are in dock. This dose is proportional to the time spent in the dock area and the surrounding population density.

3.4 Results

The radiological consequences code, METRAN, quantifies the accident-free environmental impacts resulting from the transport of standard shipments through the New York City grid. The results are expressed by person-rem for the shipment year (1974-1975) considered. These radiological impacts are analyzed with respect to end-use, transportation mode, and package type. Radiological impacts on the respective population groups at risk are interpreted and discussed.

3.4.1 Accident-Free Radiological Impacts by End-Use

Radiological impacts resulting from accident-free transport in the urban study area are summarized by end-use in Table 5. A total of 786 person-rem is found for the analysis.

Radioisotopes having various medical uses are observed to constitute the largest component (87.3%) of the accident-free risk. This result is reasonable since Table 2 shows that radioisotopes having medical uses comprise more than 80% of the yearly shipments and nearly 79% of the annual TI.

TABLE 5

Accident-Free Transport Impacts by End-Use

End-Use	Person-Rem/Year	Percent of Total
Medical	686	87.3
Industrial	97.6	12.4
Fuel Cycle	0.227	2.9×10^{-2}
Waste	1.44	0.2
Total	786	~ 100%

Industrial applications constitute the next important contributor (12.4%) to the radiological impact from accident-free transport. This result is also expected since Table 2 shows that 11% of the shipments in the urban area involve industrial-use radioisotopes and 16% of the total standard shipments TI, have industrial end-use.

Nuclear fuel cycle shipments and shipments of radioactive waste account for the remaining .3% of accident-free radiological impacts. The small contribution from the waste category is largely explained by the small number of shipments applicable to the urban region during the survey year. The nuclear fuel cycle shipments considered largely involve transport of fresh fuel to reactors by barge (see Appendix A), which does not contribute to the dose received by urban population groups.

The impacts of doses received by urban population groups are summarized by end-use in Table 6. It can be observed that transportation of medical-use isotopes principally results in exposure to handlers, truck crew, people in air terminals, and warehousemen. Less than 4% of the total annual dose is received by people in vehicles; less than 1% of the total annual person-rem is accumulated by either pedestrians or by people in buildings. Industrial sources lead to exposure of surrounding population groups in descending order of annual radiological consequences: handlers, people in air terminals, warehousemen, and crew. Warehousemen receive a greater dose relative to crew for industrial sources than for medical-use shipments because a larger percentage of industrial material is stored. Fuel cycle and waste shipments result in small doses being received by the truck crew, people in vehicles, people in buildings, and pedestrians.

3.4.2 Accident-Free Radiologial Impacts by Transport Mode

Accident-free transport impacts by transport mode are summarized in Table 7. The predominant contributor to radiological impact in the urban area is truck transport. Trucks carrying radioactive materials in combination with air passenger service constitute the major shipment mode in terms of annual radiological consequences from accident-free transport. Trucks alone and trucks in combination with air freight service rank second and third respectively as contributors to accident-free transport impacts. Air passenger overflights are responsible for less than 1% of the accident-free impact.

TABLE 6

Accident-Free Radiological Impacts (Person-rem/Shipment Year) to Population Groups in Urban Areas by End-Use

End-Use	Handlers	Warehouse-men (Storage)	Crew (Truck)	Pedes-trians	People in Vehicles	People in Buildings	People in Rail Depots	People Sharing Rail Link	People in Rail Right-of-Way	Air Passenger Terminal	Air Cargo Terminal	Ship	Totals
Medical	292.24	85.73	150.34	5.10	18.43	5.18	—	—	—	128.87	—	—	685.9
Industrial	45.18	16.34	12.02	.256	.784	.364	—	—	—	23.00	—	—	97.9
Fuel Cycle	—	—	.17	.0057	.0286	.0182	—	—	—	—	—	—	0.2
Waste	—	—	1.15	.039	.178	.025	—	—	—	—	—	—	1.4
Total	337.42	102.07	163.68	5.40	19.42	5.63	—	—	—	151.87	—	—	786

TABLE 7

Accident-Free Transport Impacts by Mode

Shipment Mode	Person-Rem/yr	Percent of Total
Air passenger with secondary mode truck	384	48.9
Truck	244.5	31.1
Air freight with secondary mode truck	150.9	19.2
Air passenger, overflight only	6.1	0.8
Air freight, overflight only	--	-
Ship	--	-
	786	100

The distribution of accident-free doses to urban population groups as a function of transport mode is detailed in Table 8. The doses to people in air terminals, handlers, warehousemen, and truck crews dominate the impacts associated with air-passenger flights with truck secondary modes. Truck through-shipments of radioactive material result in exposure principally to the crew, handlers, and to people in other vehicles; smaller doses are received by pedestrians and people in buildings. Transport of radioactive material by air freight with truck as a secondary mode results in dose to handlers and, to a smaller extent, truck crews. Routes associated with air passenger overflights carrying radioactive material lead to small exposures to people in the air terminal and to warehousemen.

3.4.3 Accident-Free Radiological Impacts by Package Type

A summary of accident-free impacts by package type is presented in Table 9. The vast majority of annual person-rem is attributable to lightly-shielded type A packages containing radioactive material. Type B packages and drums account for the remaining 2.4% of the radiological environmental impact. Many of these packages were transported by barge through the grid and therefore did not expose, for example, the large number of people adjoining routes followed by trucks carrying type A packages.

TABLE 8

Accident-Free Radiological Impacts (Person-rem/Shipment Year) to Population Groups in Urban Areas by Shipment Mode

Mode	Handlers	Warehouse-men (Storage)	Crew (Truck)	Pedes-trians	People in Vehicles	People in Buildings	People in Rail Depots	People Sharing Rail Link	People in Rail Right-of-Way	Air Passenger Terminal	Air Cargo Terminal	Ship	Totals
Air passenger with secondary mode (truck)	113.16	99.54	21.50	.152	.262	1.06	--	—	—	148.31	—	—	384.0
Truck	94.38	—	122.69	5.15	18.74	3.55	—	—	—	—	—	—	244.5
Air freight with secondary mode (truck)	129.88	--	19.49	.099	.417	1.02	—	—	—	—	—	—	150.9
Air passenger, overflight only	—	2.53	--	—	—	—	—	—	—	3.56	—	—	6.1
Air freight, overflight only	—	--	—	—	—	—	—	—	—	—	—	—	—
Ship	—	--	--	—	—	—	—	—	—	—	—	—	—
Totals	337.42	102.07	163.68	5.40	19.42	5.63	--	—	—	151.87	--	—	786

TABLE 9

Accident-Free Transport Impacts by Package Type

Package Type	Person-rem/year	Percent of Total
A	767	97.6
B	17.4	2.2
Drum	1.54	0.2
Cask	0.0279	--
Limited	--	--
Total	786	

The distribution of doses to urban population groups as a function of radioactive material package type is described in Table 10. Type A packages are principally associated with doses to handlers, to truck crews, and to people in air terminals; smaller doses are received by people in vehicles, by people in buildings, and by pedestrians. Handlers, people in air terminals, warehousemen, and crew receive the bulk of the dose associated with transportation in type B packages. Dose to crew is the most appreciable impact from shipment in drums or in casks.

TABLE 10

Accident-Free Radiological Impacts (Person-rem/Shipment Year) to Population Groups in Urban Areas by Package Type

Package Type	Handlers	Warehouse-men (Storage)	Crew (truck)	Pedes-trians	People in Vehicles	People in Buildings	People in Rail Depots	People Sharing Rail Link	People in Rail Right-of-Way	Air Passenger Terminal	Air Cargo Terminal	Ship	Totals
A	329.24	98.95	160.82	5.33	19.15	5.47	—	—	—	147.73	—	—	767
B	8.10	3.12	1.87	.0379	.111	.0845	—	—	—	4.14	—	—	17.5
Drum	.082	—	.984	.0331	.150	.0616	—	—	—	—	—	—	1.3
Cask	--	--	.010	.0004	.0046	.013	—	—	—	—	—	—	0.03
Totals	337.42	102.07	163.68	5.40	19.42	5.63	—	—	—	151.87	—	—	786

3.4.4 Summary of Impacts from Accident-Free Transport

The impact from accident-free transport of radioactive material in the urban area is summarized in Table 11 by person-rem per shipment year for the exposed population groups. These groups, in descending order of annual radiological impact are: handlers, truck crews, people in passenger air terminals, warehousemen, people in vehicles, people in buildings, and pedestrians. More than 96% of the impact is distributed among the first four of these dose groups. People in buildings and pedestrians each account for less than 1% of the total annual radiological impact in the urban area.

A total of 786 person-rem were estimated for the New York City analysis of accident-free impact. Using 25 expected latent cancer fatalities per 10^6 person-rem (see Appendix H) for the low-dose, low-dose-ratio typical of accident-free transport conditions, yields a prediction of .0196 latent cancer fatalities per shipment year.

The value of 786 person-rem for the 2.82×10^5 packages considered in the New York City study area can be scaled upwards by the 2.19×10^6 packages included in the nationwide analysis performed in Reference 1. This rough scaling would predict a value of 6104 person-rem for the country, which compares favorably with the 9790 person-rem estimated without regard to the special shielding aspects of urban environs to external penetrating radiation.

TABLE 11

Summary of Impacts from Accident-Free Transport

Dose Group	Total Person-rem/yr	Percent of Total
Handlers	337.4	43.0
Crew	163.7	20.8
Passenger Air Terminal	151.9	19.3
Storage	102.1	13.0
People in Vehicles	19.4	2.5
People in Buildings	5.6	0.7
Pedestrians	5.4	0.7
People in Rail Depots	--	--
People Sharing Rail Transport Link	--	--
People in Rail Right-of-Way	--	--
Cargo Air Terminal	--	--
Ship	--	--
	786	100

REFERENCES

1. NUREG-0170.

2. NUREG-0073.

3. Environmental Survey of Transportation of Radioactive Materials to and from Nuclear Power Plants, WASH-1238, USAEC, December 1972.

4. Shapiro, J., "Exposure of Airport Workers to Radiation from Shipment of Radioactive Materials," NUREG-0154, USNRC, January 1977.

CHAPTER 4

IMPACTS OF TRANSPORTATION ACCIDENTS INVOLVING RADIOACTIVE MATERIALS IN URBAN AREAS

4.1 Introduction

Two factors must be considered in evaluating the impact of accidents which involve vehicles carrying radioactive shipments: probability and consequence. The probability that an accident releasing radioactive material will occur can be defined as expected number of accidents of given severity per year for each transport mode together with package response to those accidents and the dispersal or exposure that is expected. The consequence of an accident is defined as the effect of the release of a specified quantity of dispersible radioactive material to the environment, or the exposure resulting from damaged package shielding. The probability and consequence terms are tied together by a package response factor which describes the amount of material released.

The product of probability, consequence, and package response is defined as the expected value of radiological risk, and is expressed in terms of expected radiological consequences per shipment year. This risk can be quantified for each shipment type; and, by summing overall shipments, the annual radiological risk resulting from accidents involving all shipments can be computed. The value obtained for "expected annual radiological accident risk" represents the total number of each specific type of health effect which is expected to occur over all time following the year of shipping activity. Since this method does not distinguish high probability/small consequence risks from low probability/large consequence risks, shipments with potentially severe consequences are considered separately. In some instances, these "worst-case" shipments occur within the NYC data base and so are included in the expected value risk calculation. In some cases, a "what if ..." approach was used for shipments not included in the NYC data base and the shipment does not contribute to the expected value of risk.

Accident risk is calculated using the accident portion of the METRAN computer code discussed in Appendix E. Figure 4-1 outlines the information flow used in these calculations. Nonradiological impacts of transportation accidents involving radioactive materials are discussed in Chapter 7.

This chapter is divided into 6 additional sections. Section 4.2 addresses accident rates, accident severity categorization, and package release fractions. Section 4.3 discusses the dispersion/exposure models. The results of the risk calculations using the standard shipments are presented in Section 4.4. Section 4.5 discusses the potential effects and clean-up costs of the radioactive contamination from a transportation accident. In Section 4.6, high consequence/low probability accident scenarios are considered. Section 4.7 compares results from METRAN with consequence calculations made using an independent computer model. Section 4.8 summarizes the results of the accident risk and consequence calculations.

The methodology for this section is strongly based on techniques developed in References 1 and 2. In general, the techniques are merely outlined in this chapter. Details can be found in the appendices to this document.

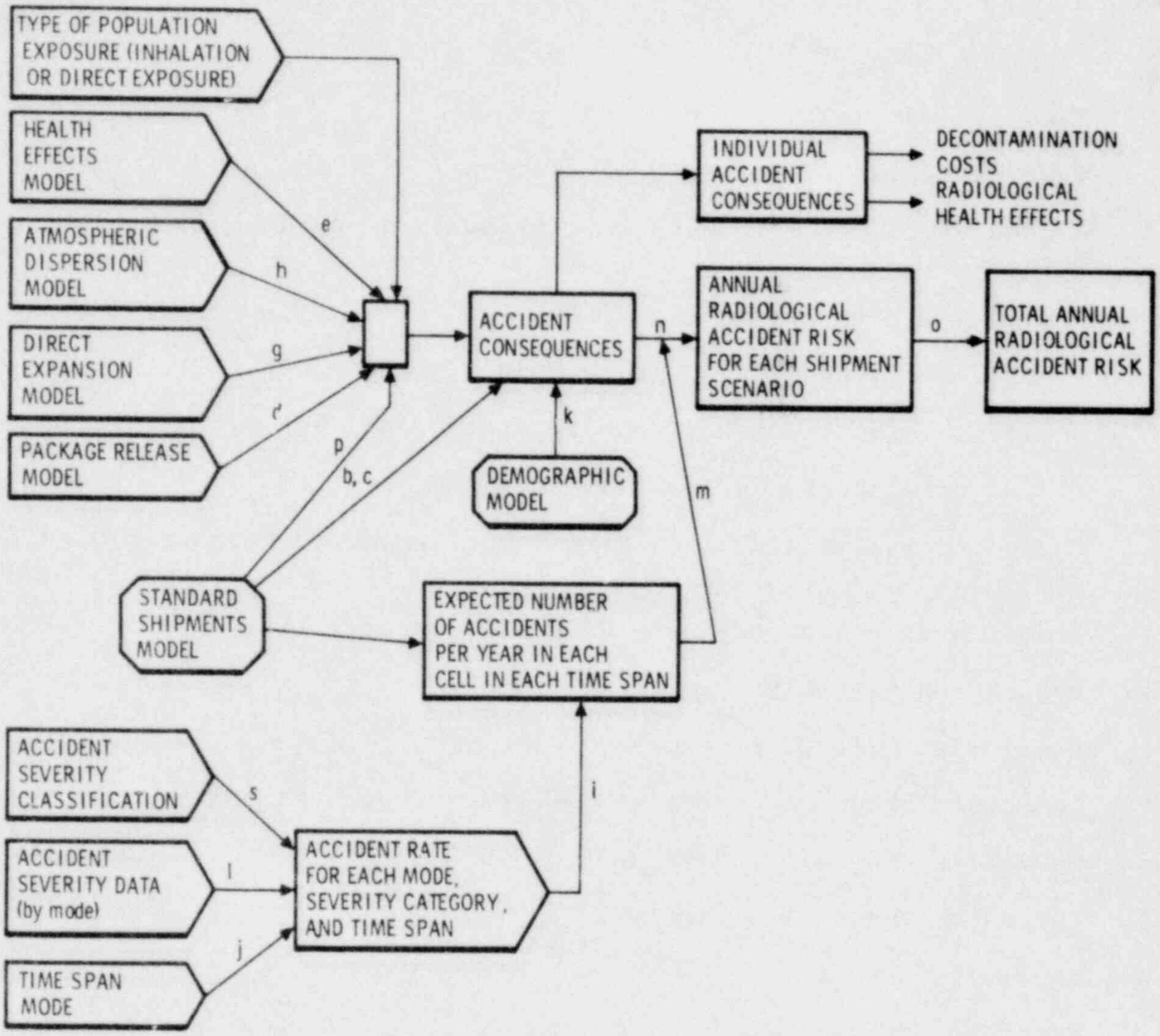

Figure 4-1. Flow Diagram for Accident Analysis

Figure 4-1 (cont.)

NOTES:

a. Shipment mode.

b. Type of packaging.

c. Type of radionuclide; size of shipment.

d. Amount of dispersible material released, or amount of unshielded material.

e. Dosimetric data for radionuclide.

f. Overall accident rate for each mode.

g. Accident rate for each mode - severity combination.

h. Amount of dispersible material inhaled.

i. Number of shipments per year; shipment route through grid; and start time.

j. Fraction of urban accidents occurring in each time span.

k. Population densities.

l. Biological effects of exposure.

m. Expected number of accidents per year of each severity.

n. Summation over all severities.

o. Summation over all scenarios.

p. Physical form.

q. External exposure dose vs. distance.

r. Dosimetry of accident.

s. Description of accident severity classes for all transport modes.

4.2 Accident Rates, Severity, and Package Release Models

Direct radiological effect on man may result from accidents involving any mode of transportation. The probability that a transport vehicle will be involved in an accident of a specific severity is dependent upon the accident rate per vehicle-kilometer, the number of shipments per year by that mode, and the number of kilometers traveled by each shipment. The consequences of an accident depend on the quantity and type of radioactive material present, the fraction of the material released, the population density in the cells affected by the release, the local meteorology at the time of the accident, and the radiobiological effect of the material.

4.2.1 Accident Rates

In order to compute accident probabilities, it is first necessary to know the overall accident rate for each transport mode. The accident rates used in this assessment are specified on a per vehicle-kilometer basis and are summarized in Table 4-1. Details on the determination of these rates are in Section 8 of Appendix A.

TABLE 4-1

Accident Rates*

Mode	Accident Rate (per vehicle-kilometer)
Aircraft	1.44×10^{-8}
Motor Vehicles	1.06×10^{-6}
Train**	$.93 \times 10^{-6}$
Ship, Barge	6.06×10^{-6}

*Methods for determining these values and references used are provided in Section 8 of Appendix A.

**Rail accidents are given as rail-car accidents/ rail-car kilometer.

4.2.2 Accident Environment Severity Classification

The amount of radioactive material released to the environment in an accident depends upon the strength of the packaging and the severity of the accident. Very severe accidents might be expected to release a considerable amount of the radioactive material carried, while minor accidents are unlikely to cause any release. In addition to the overall accident rate for each mode, the distributions of accidents according to severity must be determined. Numerical distributions of accidents according to severity for air, truck, rail, and waterborne transport are provided in Section 8 of Appendix A. In addition, estimates of the distribution of motor vehicle accidents by time-of-day are discussed. Values for accident severity fractions for each mode and time span are given in Table 4-2 at the end of this section.

4.2.2.1 Aircraft Accidents

The classification devised for aircraft accidents follows that of Clarke, et al[3] and is illustrated in Figure 4-2. The ordinate is the speed of impact onto an unyielding surface, and the abscissa is the duration of a 1300°K fire. This temperature was chosen to facilitate comparison with previous data,[3] and roughly corresponds to that of a jet fuel fire. Data[3,4] indicate that impact speed and fire duration are the most significant parameters with which to categorize aircraft accidents and that crush, puncture, and immersion are lower order effects. Impacts onto unyielding surfaces rather than real surfaces were chosen in order to make use of this data and to facilitate comparison with regulatory standards. A derating model was introduced into the analysis to account for the probability of impact on real surfaces rather than on unyielding targets.

The first two scale divisions for impact speed were chosen to correspond to standards for type A and type B packagings, respectively. Thus, a Category I accident with no fire, equivalent to a drop from 4 feet (1.2 m) or less onto an unyielding surface, should not produce a loss of containment or shielding in a type A package. The division between a Category II and Category III impact accident was set at a 30-foot (9.1 m) equivalent drop to correspond to the type B container test specification.

The fire duration categories are chosen so that, with the exception of certain Category IV accidents, increasing the fire duration by 30 minutes is equivalent to increasing the impact to the next higher level. Impacts at less than 48 k/hr would not be sufficient to produce an accident of Category V or greater regardless of how long the fire burned.

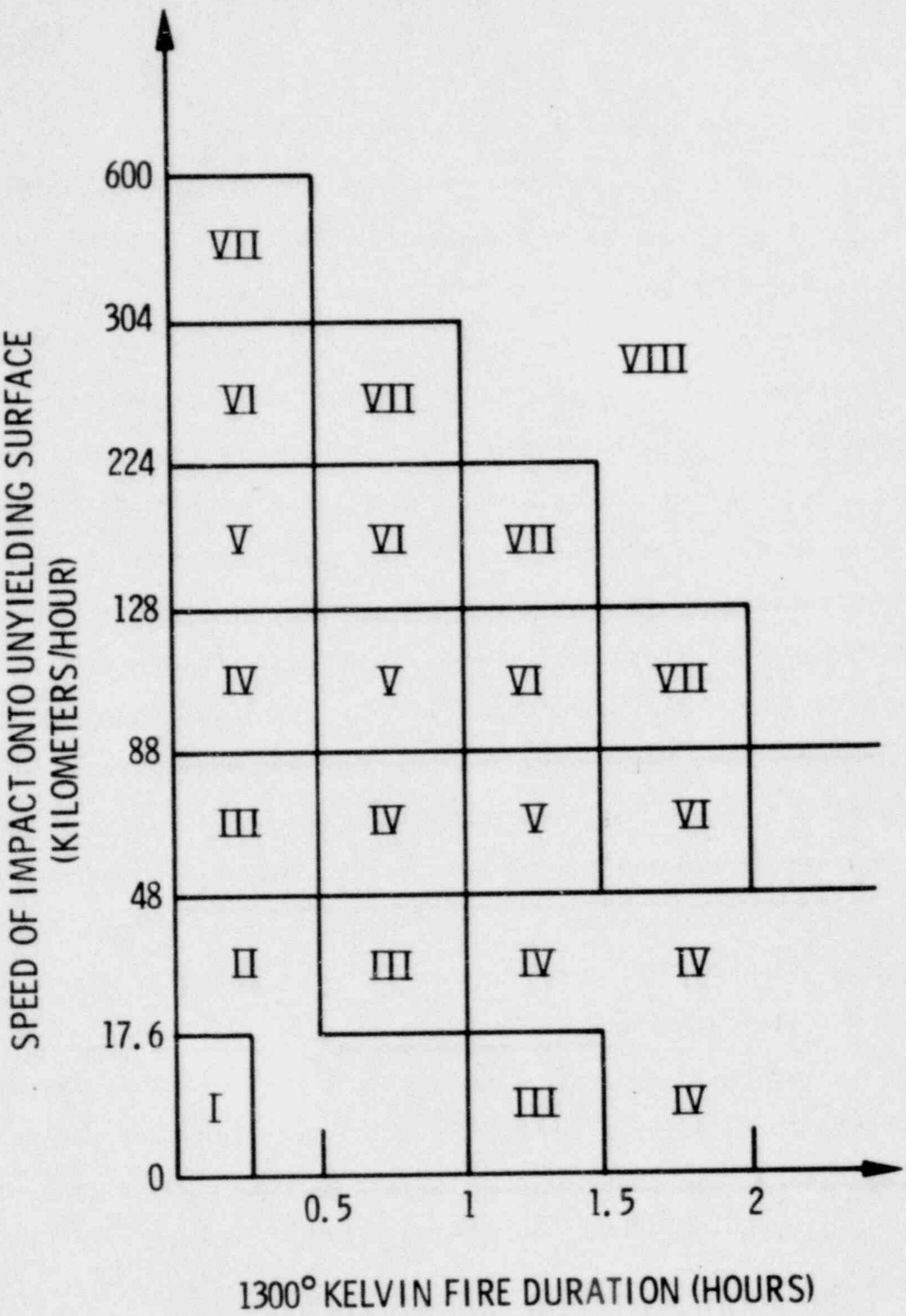

Figure 4-2. Accident Severity Category Classification Scheme - Aircraft

Note that Category I accidents can involve a fire lasting up to fifteen minutes. A type A package involved in a Category I accident in which a fire occurs would not be required by the regulations to survive the accident without loss of shielding or containment.

Most aircraft accidents involve impact forces which are less severe than would occur on the unyielding surface used as a basis for the aircraft accident data, because most surfaces yield or deform to provide at least some cushioning effect. The fractional occurrences for aircraft accidents are obtained by reducing those fractions used for unyielding surfaces in consideration of occurrence statistics for real surfaces of varying hardness. (The details of and rationale for this procedure are discussed in Section 8 of Appendix A.) This reduction procedure was applied to Categories III through VIII. No real surface derating is expected for Categories I and II, since these low-severity accidents involve low impact velocities and are expected to occur while the aircraft is on the ground.

4.2.2.2 Motor Vehicle Accidents

The severity classification for motor vehicle accidents is shown in Figure 4-3. In this case the ordinate is crush force. Clarke et al[5] have shown that in the case of accidents involving motor carriers, the dominant factors in the determination of accident severity are crush force, fire duration, and puncture. The crush force may result from either an inertial load (e.g., container crushed upon impact by other containers in load) or static load (e.g., container crushed beneath vehicle). Since impacts are not directly involved, no derating is applied.

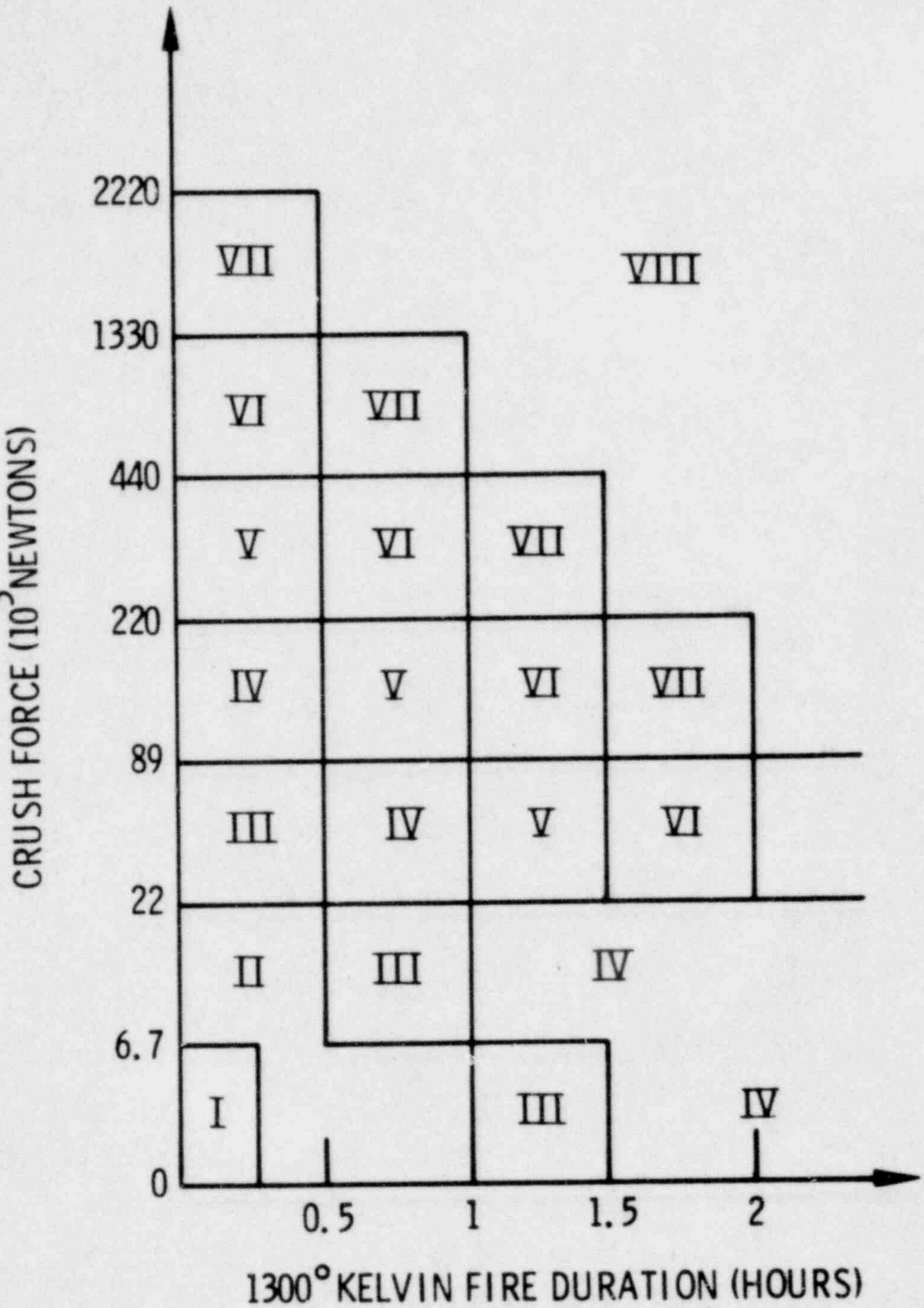

Figure 4-3. Accident Severity Category Classification Scneme - Motor Vehicles

4.2.2.3 Train Accidents

Figure 4-4 illustrates the accident severity classification used for train accidents. The ordinate in this case is puncture and impact velocity. As with truck accidents, no real-surface derating of the fractional occurrences is required, since puncture is the predominant mode of damage in severe accidents. In their analysis of train accidents, Foley, et al[6] considered crush to be an important factor. However, they were concerned with containers shipped in carload lots and with the crush forces resulting from interaction with other cargo in the rail car.

Rail cars specifically designed to carry a single large cask behave somewhat differently under accident conditions[7] in that the impact rather than puncture is the significant deformation force. Cask car accident fractions by severity are based on the methodology of References 7 and 8.

4.2.2.4 Ship and Barge Accidents

Records for calendar year 1973 for domestic waterborne traffic show a total of 6.67×10^{11} ton-miles of water traffic of which approximately 26 percent (or 1.73×10^{11} ton-miles) was barge traffic.[9] According to the Coast Guard's annual statistics of casualties, there were an estimated 1395 barge accidents in 1973, of which about 60 percent involved cargo barges.

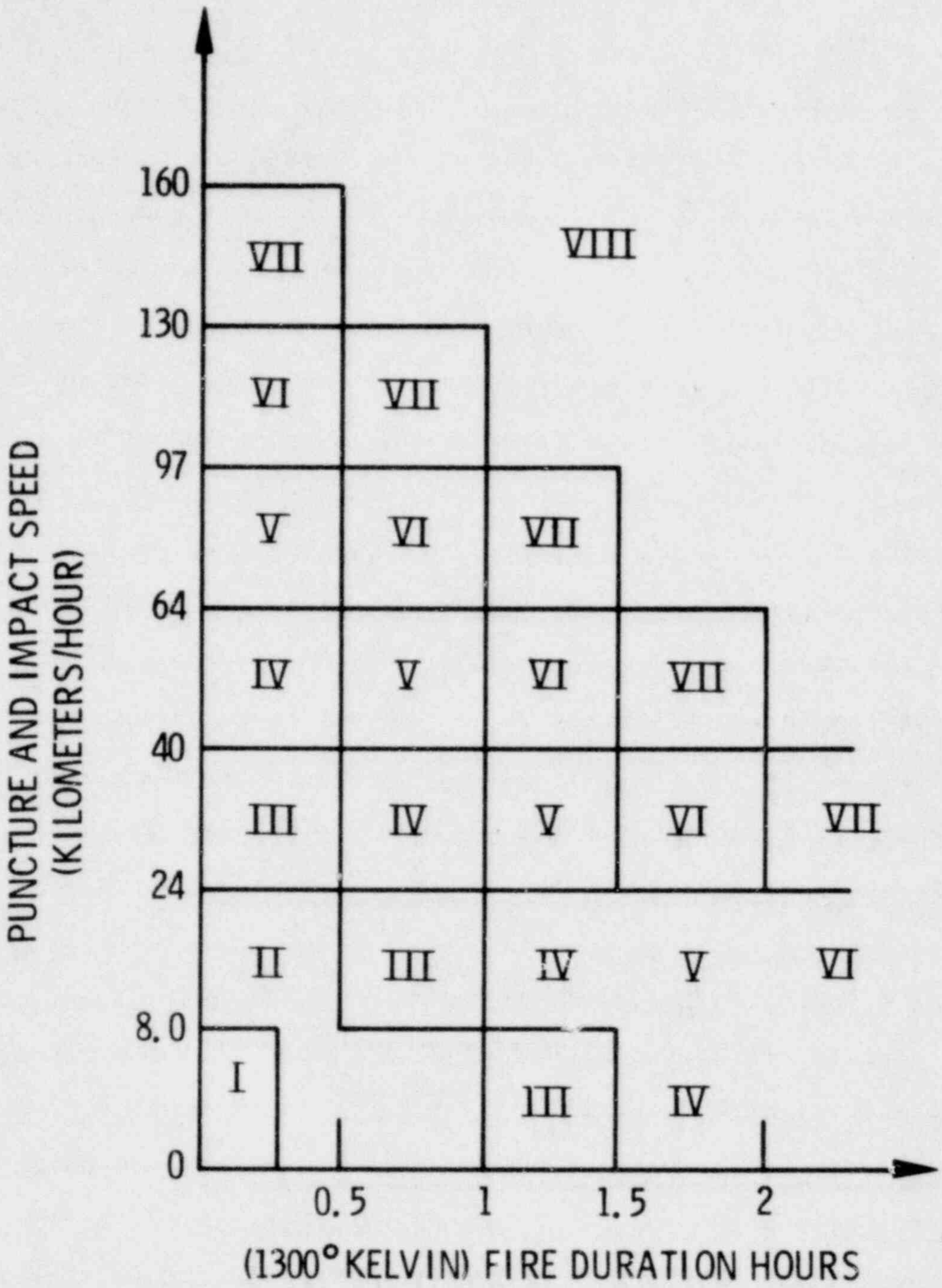

Figure 4-4. Accident Severity Category Classification Scheme - Train

The available data cannot be analyzed in the same way as the data for rail or truck transport. The estimated average net cargo weight of a typical barge is about 1200 tons. The total number of barge miles would then be about 1.44×10^8. This yields an accident rate of about 6 per million barge-miles.

Very little data is available on the severity of accidents involving barges. Since barges travel only a few miles per hour, the impact velocity in accidents is small. However, because of the mass of the vehicle and cargo, packages can encounter large forces. A forward barge could impact on a bridge pier and suffer crushing forces due to other barges being pushed into it. A coastal or river ship could knife into a barge. Fires could result in either case. An extreme accident, i.e., an extreme impact plus a long fire, is considered to be of such low probability that it is not considered a design-basis accident. The likelihood of cargo damage occurring in barge accidents is much less than in the case of rail accidents.

A cask accidentally dropped into water during barge transport is unlikely to be adversely affected unless the water is very deep. A recent study[10] concluded that the pressure seals on a spent-fuel cask dropped into the ocean might begin to fail, releasing contaminated coolant, at a depth of 200 meters, a typical depth at the edge of the continental shelf, and much deeper than urban harbors or inland waterways. Considering the low probability of occurrence, the relatively shallow harbor depths, the small amount of commercial fishing in urban areas, and the dilution that would be available, there would be little environmental impact from single events of this kind.

4.2.2.5 Accident Survey Summary

Accident fractions for each mode and severity category are summarized in Table 4-2. Details on methods used to obtain these values can be found in Appendix A.

4.2.3 Release Fractions

In order to assess the risk of a transportation accident, it is necessary to predict the fraction of the total package contents which would be released from an accident of a given severity. The actual releases for a particular package type would not necessarily be the same for a number of accidents of the same severity class. In some cases there may be no release, while in others there may be, for example, a 10 percent release. Indeed, in an accident involving a number of radioactive material packages transported together, some of the packages may release part of their contents while others have no release at all. The approach taken in this assessment is identical to that used in Reference 1 where point estimates are used for the average release fraction for each severity category and package type, and where it is assumed that all such packages, including each package in a multipackage shipment respond to such an accident in the same way regardless of contents. In addition, it is assumed that an accident of a given severity produces the same release fraction for a specific package type regardless of transport mode. Although this assumption appears to directly equate crush force, impact, and puncture, it actually assumes that the release from a specific impact accident will equal the release from a crush or puncture accident. This equality is made by appropriate assignment of the fractional occurrence by severity for each mode.

TABLE 4-2

Summary of Accident Severity Fractions
for All Transport Modes

Severity Category	Mode				
	Motor Vehicle	Aircraft*	Rail-Boxcar	Rail-Cask Car	Water Modes
I	.714	--	.5	.45	.897
II	.23	--	.3	.34	.0798
III	.044	--	.18	.15	.00113
IV	.010	.03	.018	.056	.0186
V	.0021	.04	.0018	2.6×10^{-5}	5.2×10^{-6}
VI	.00083	.024	1.3×10^{-4}	1.1×10^{-5}	7.2×10^{-5}
VII	6.4×10^{-5}	.0019	6×10^{-5}	2.7×10^{-5}	1.95×10^{-5}
VIII	1.13×10^{-5}	.0003	1×10^{-5}	6.2×10^{-6}	1.3×10^{-5}

*Since only overflights are included, no Category I, II, or III accidents are considered since these are pre- or post-flight accidents occurring on the ground.

The paucity of data on package responses to severe accidents makes it difficult to predict even the average release fraction, much less a distribution. Packaging standards do not require testing to the point of package failure. Therefore, until recently, there has been little information relating the response of packages to accident environments.

A series of severe impact tests were carried out using several types of containers commonly used to ship plutonium and spent fuels.[11,12,13] Tests of plutonium containers revealed structural damage to the inner container after impact onto unyielding targets at speeds up to those typical of a Category V impact accident. Several containers exhibited some minor structural damage and cracking in Category VI impacts, but no verified release occurred. Tests of typical commercial containers showed the failure of a non-specification cast iron plug, material loss, and compromise of the overall integrity of the inner containers. In one set of tests, a container was estimated to have lost 6 percent of its contents (magnesium oxide powder) in a Category VII impact, while others survived Category VIII impacts with no loss of contents. Although none of the containers in this test series were subjected to fire, others of the same type survived less severe impacts followed by a 1300°K environment lasting for 30 minutes with no release.

The responses of packages are estimated using either this test information or assuming that packaging begins to fail at levels just above those they are required by regulations to survive. The release fraction estimates for all packagings evaluated are shown in Table 4-3. A more detailed derivation of these values for each package type is contained in Chapter 5 of Reference 1.

TABLE 4-3

Release Fractions

Severity Category	LSA Drum	Type A	Type B No Pu	Type B 1975 Pu	Cask (exposure)	Cask (release)
I	0	0	0	0	0	0
II	.01	.01	0	0	0	0
III	.1	.1	.01	0	0	.01
IV	1.0	1.0	.1	0	0	.1
V	1.0	1.0	1.0	0	0	1.0
VI	1.0	1.0	1.0	.01	$3.18x10^{-7}$	1.0
VII	1.0	1.0	1.0	.05	$3.18x10^{-5}$	1.0
VIII	1.0	1.0	1.0	.1	$3.12x10^{-3}$	1.0

4.3 Dosimetric Model

Once a release occurs, the released material drifts downwind and disperses. It can produce such environmental effects as internal and external radiation exposure, contamination, or buildup in the food chain.

Environmental impact can result either from a release to the atmosphere or from direct external radiation exposure. Atmospheric transport and diffusion can disperse released material over large areas; but the degree of dispersal is determined by atmospheric turbulence which is a function of season, time of day, amount of cloud cover, surface characteristics, and other meteorological parameters. The dispersion of radionuclides associated with the passage of a cloud of released material can have a very complex environmental impact, particularly on man, as illustrated in Figure 4-5. Direct external or internal dose to man is the principal effect from gamma-emitting radionuclides. Radionuclides which emit alpha or beta radiation produce significant radiological consequence when inhaled. Figure 4-5 shows that deposited radionuclides can also be taken into the food chain (transferred from soil to vegetation to animals and eventually to man). However, radiation doses to man through the food chain are usually more significant (relative to doses through inhalation, for example) only if a continuous source of release exists. This is particularly true of an urban release, since only a small amount of urban area is devoted to agriculture likely to lead to food chain buildup.

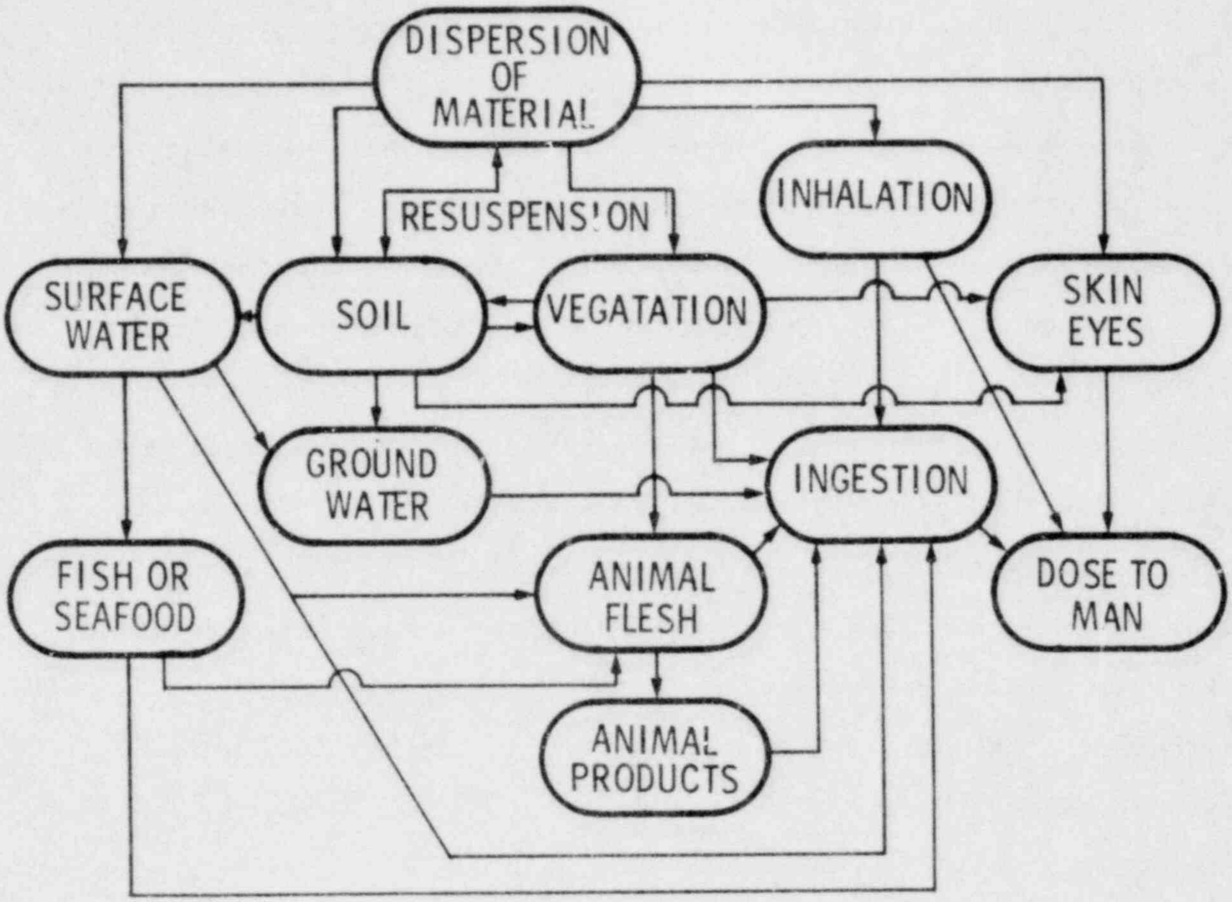

Figure 4-5. Possible Routes to Man from Radionuclide Release

4.3.1 Atmospheric Dispersion Models

The analysis of atmospheric dispersion in the urban area centers around two submodels--MICMET and PICMET. The MICMET model, discussed in detail in Appendix F, is used to analyze the behavior of a cloud of aerosolized debris in the immediate vicinity of the release point. It uses a three-dimensional layered Gaussian formulation and includes explicit consideration of street canyon eddy effects and possible multiple cloud formation. The PICMET model, discussed in detail in Appendix G, uses MICMET output on cloud dimension and concentration as the input to a particle-in-cell diffusion model. In this model, particles are initially "loaded" into the PICMET cloud at random and are then allowed to move in response to various forces including local winds, turbulence, and gravitational settling. The meteorological data bases, discussed in Section 10 of Appendix A, consist of actual wind speeds and directions taken from a study conducted to evaluate SO_2 pollution in the New York area.[14]

4.3.2 External Exposure Model

If the postulated accident results in shielding damage to a package containing a non-dispersible material, e.g., one of the special-form shipments such as Co-60 and Ir-192, or an irradiated fuel cask, direct external exposure can result from gamma or neutron radiation emitted by the material. This assumes that the source remains at the accident site for some period of time (called accident delay) with no evacuation and no introduction of temporary shielding. This calculation is discussed in Appendix E.

4.3.3 Dose Calculation

Quantification of several separate dose components is necessary to specify the consequence of a given accident. These components include:

1. Dose due to inhaled radionuclides: the dose received by persons who inhale material as the cloud of aerosolized debris passes. This dose is only calculated if the material is considered dispersible.
2. Cloudshine dose: the dose received by persons who are exposed to external-penetrating radiation from the cloud. This, too, occurs only if the material is dispersible, and is considered to occur only to people who are immersed in the cloud.
3. Remnant dose: the external-penetrating radiation dose received by people who remain near an accident site where a significant amount of released, non-aerosolized, material is present. This is only calculated for accidents involving dispersible material.
4. Special-form accident dose: the external-penetrating radiation dose received by people who are in the vicinity of an accident involving a shielding loss of a shipment of special-form (i.e., nondispersible) material.
5. Nonrelease accident dose: the external-penetrating radiation dose received by people in the vicinity of an accident severe enough to delay the vehicle but not severe enough to damage the packaging. This dose is essentially an additional accident-free dose caused by the delay of the vehicle in a populated area.

The detailed mathematical descriptions of each of these dose groups are provided in Appendix E.

Once computed, doses must be translated into health effects. As discussed in Appendix H, four health effects are considered: early fatalities, early morbidities, latent cancer fatalities, and genetic effects. Doses 1, 2, 3, and 4 have the potential for causing early fatalities or morbidities, which are threshold effects. All five have the potential to cause latent cancers and genetic effects, since empirical dose-effect relationships are not used.

Once the expected number of health effects has been calculated, it can be expressed as either individual consequence or risk.

4.4 Radiological Risks from Standard Shipments

In order to evaluate the expected value of radiological risks, it is useful to present the information from several different perspectives and then tie that information together. Initially, the entire shipments model is examined. The model is subsequently broken down on a per-shipment basis.

In evaluating these results, the reader should keep three concepts in mind. First, the "expected value of annual radiological risk," as defined in this report, is the number of a particular type of health effect expected to occur after a period of shipment at a particular level. It is not necessarily the number of health effects expected to occur annually. Second, the population "at risk" from shipments of radioactive material is composed of essentially all persons residing in the urban area, since, theoretically, the cloud of aerosolized material from an accident could pass through any portion of the city, given the required meteorological conditions. Third, the "exposed population" is that portion of the population at risk directly affected by the radiation or radioactive debris from a specific release.

The computed numbers of health effects presented in the table of Section 4.4 are expected values of annual radiological risk. These values represent the number of health effects which are statistically predicted to occur within the population risk as a result of a given year's shipment activity at a specified level.

Table 4-4 shows the risk values from an end-use viewpoint. As will be discussed later, the risk is dominated by low severity releases. Therefore, isotopes for medical use with their large numbers of shipments are the most significant single source.

TABLE 4-4

End-Use Contributions to Expected Value of Radiological Risk

End-Use	Amount Shipped (ci/yr)	f*	No. of Shipments	f	Expected Latent Cancer Fatalities	f	Expected Genetic Effects	f	Expected Early Morbidities	f	Expected Early Fatalities	f
Medical	4.65×10^5	.12	2.27×10^5	.81	2×10^{-3}	.64	5.5×10^{-3}	.75	---	-	---	-
Industrial	7.2×10^5	.19	3.1×10^4	.11	3.2×10^{-4}	.10	1.1×10^{-3}	.15		-	---	-
Fuel Cycle	2.61×10^6	.69	2.3×10^4	.08	8.6×10^{-4}	.27	6.2×10^{-4}	.09	6.8×10^{-4}	1.0	1.9×10^{-5}	1.0
Waste	.06	-	960	-	---	-	---	-	---	-	---	-
Total	3.8×10^6		2.8×10^5		3.2×10^{-3}		7.3×10^{-3}		6.8×10^{-4}		1.9×10^{-5}	

*f = fraction of contribution to expected value of radiological risk.

Table 4-5 displays risk from a mode viewpoint. In this case, since virtually all of the air and truck risk derives from the truck link, the contribution of truck mode to the expected number of latent cancer fatalities and genetic effects correlates well with the total number of shipments by truck.

Table 4-6 displays risk from a package type viewpoint. Type A packages dominate the risk because of the large number of relatively small medical-use shipments made in type A packages.

In general. the results are more closely correlated with the number of packages shipped than with the number of curies shipped. In order to partially account for this, Table 4-7 shows a breakdown by shipment categorization.

Each standard shipment was assigned to one of the five listed categories which specify curie size and dispersibility. The majority of curies are shipped in nondispersible form. However, shipments of this sort contribute relatively little to overall health effects for two reasons. First, they are shipped in large accident-resistent packaging with low release fractions in the accident rate severity categories; second, the direct exposure mode resulting from an accident does not involve population exposure comparable to inhalation of a radioactive material. As a result, over 90% of the accident risk results from shipment of dispersible materials, with more than half of that risk coming from shipments containing less than 2 curies.

TABLE 4-5

Contributions of Transport Modes to Expected Value of Radiological Risk

Transport Mode	Amount Shipped (ci/yr)	f	No. of Shipments	f	Expected Number of Latent Cancer Fatalities	f	Expected Number of Genetic Effects	f	Expected Number of Early Morbidities	f	Expected Number of Early Fatalities	f
Truck	3.27×10^6	.86	1.52×10^5	.54	9.3×10^{-4}	.29	8.2×10^{-4}	.11	6.8×10^{-4}	1.0	1.9×10^{-5}	1.0
Air*	5.6×10^5	.14	1.1×10^5	.38	—	-	—	-	—	-	—	-
Air and Truck**					2.2×10^{-3}	.68	5.9×10^{-3}	.80	—	-	—	-
Ship	48.5	-	2.31×10^4	.08	9.0×10^{-5}	.03	6.2×10^{-4}	.08	—	-	—	-
Total	3.8×10^6		2.8×10^5		3.2×10^{-3}		7.3×10^{-3}		6.8×10^{-4}		1.9×10^{-5}	

*Air Freight and Passenger Air are combined.

**Virtually all of the risk from this mode combination derives from the truck link.

TABLE 4-6

Contribution of Package Type to Expected Value of Radiological Risk

Package Type	Amount Shipped (ci/yr)	f	No. of Shipments	f	Expected Number of Latent Cancer Fatalities	f	Expected Number of Genetic Effects	f	Expected Number of Early Morbidities	f	Expected Number of Early Fatalities	f
A	2.6×10^5	.07	2.53×10^5	.90	1.9×10^{-3}	.60	6.3×10^{-3}	.86	—	-	—	-
B	6.43×10^5	.17	2.68×10^4	.10	5.3×10^{-4}	.17	1.0×10^{-3}	.14	—	-	—	-
Cask	2.64×10^6	.69	24	-	7.7×10^{-4}	.24	—	-	6.8×10^{-4}	1.0	1.9×10^{-5}	1.0
Drum	2.82×10^5	.07	760	-	—	-	—	-	—	-	—	-
Total	3.8×10^6		2.8×10^5		3.2×10^{-3}		7.3×10^{-3}		6.8×10^{-4}		1.9×10^{-5}	

TABLE 4-7

Contributions of Assigned Material Categories to Expected Value of Radiological Risk

Category	Description	Amount Shipped (ci/yr)	f	No. of Shipments	f	Expected Number of Latent Cancer Fatalities	f	Expected Number of Genetic Effects	f	Expected Number of Early Morbidities	f	Expected Number of Early Fatalities	f
1	< 2 ci, dispersible	4.37×10^4	.01	2.47×10^5	.88	1.7×10^{-3}	.52	5.6×10^{-3}	.76	—	-	—	-
2	≥ 2 ci, dispersible	1.1×10^5	.03	1.64×10^3	.01	1.1×10^{-3}	.35	2.5×10^{-4}	.03	6.8×10^{-4}	1.0	1.9×10^{-5}	1.0
3	< 2 ci, non-dispersible	2.36×10^3	-	1.21×10^4	.04	9.6×10^{-5}	.03	2.5×10^{-4}	.03	—	-	—	-
4	≥ 2 ci, non-dispersible	3.54×10^6	.93	4.22×10^3	.02	2.1×10^{-4}	.06	4.8×10^{-4}	.07	—	-	—	-
5	noble gas	1.03×10^5	.03	1.33×10^4	.05	1.2×10^{-4}	.04	8.2×10^{-4}	.11	—	-	—	-
Total	dispersible	2.59×10^5	.07	2.62×10^5	.94	2.9×10^{-3}	.91	6.7×10^{-3}	.91	6.8×10^{-4}	1.0	1.9×10^{-5}	1.0
Total	non-dispersible	3.54×10^6	.93	1.63×10^4	.06	2.8×10^{-4}	.09	6.3×10^{-4}	.09	—	-	—	-
TOTAL		3.8×10^6		2.8×10^5		3.2×10^{-3}		7.3×10^{-3}		6.8×10^{-4}		1.9×10^{-5}	

Table 4-8 shows the specific standard shipments which contribute to each of the health effect categories. Individual shipments of spent-fuel and Mo-99 account for 67% of the latent cancer fatality risk; spent-fuel accounts for all early effects; and genetic effects are distributed among several medical and industrial shipmetns, with I-131 being the largest single contributor.

A typical shipment from each of the categories of Table 4-7 was examined in detail to determine the significant contributors to the expected value of radiological risk.

Table 4-9 distributes the risk fraction by population group. Using weighted averages, one can see that people in buildings are the largest group at risk from latent cancer fatalities, whereas people in vehicles are the larges group at risk from genetic effects. Approximately 85% of the early morbidities and mortalities also occur inside buildings. This dominance of dose to people in buildings reflects two points: (1) the large number of people in buildings and, (2) the relatively minor attenuation effects caused by building ventilation systems (see Appendix E, Section 4.1.2).

TABLE 4-8

Contributions of Specific Standard Shipment to Expected Value of Radiological Risk

Latent Cancer Fatalities

Material	Route	Fractional Contribution
Spent-fuel*	17	.24
Mo-99 (1.3 ci/pkg)	15	.17
Mo-99 (1.2 ci/pkg)	1	.16
Mo-99 (91 ci/pkg)	15	.10
I-131 (.014 ci/pkg)	1	.04
I-131 (.04 ci/pkg)	15	.04
C-14 (.43 ci/pkg)	1	.03
Ir-192 (100 ci/pkg)	7	.03
Subtotal		.83
All others	-	.17

Material	Route	Fractional Contribution
Spent-fuel (inhalation)	17	1.0

Genetic Effects

Material	Route	Fractional Contribution
I-131 (.014 ci/pkg)	1	.13
C-14 (.43 ci/pkg)	1	.03
Mo-99 (1.2 ci/pkg)	1	.09
U-235 (.002 ci/pkg)	9	.09
Mo-99 (1.3 ci/pkg)	15	.06
Xe-133 (28 ci/pkg)	1	.04
P-32 (.13 ci/pkg)	15	.04
Xe-133 (28 ci/pkg)	7	.04
I-131 (.0066 ci/pkg)	4	.03
Ir-192 (100 ci/pkg)	7	.03
Mg-28 (52 ci/pkg)	15	.02
Sn-113 (.022 ci/pkg)	10	.02
Xe-133 (1.6 ci/pkg)	15	.02
Tc-99m (.037 ci/pkg)	4	.02
Subtotal		.70
All others	-	.30

*These health effects from spent fuel result entirely from inhalation. Direct exposure is not a significant contributor.

TABLE 4-9

Population Group Contribution to Expected Value of Radiological Risk

		Latent Cancer Fatalities				Genetic Effects			
Category*	Description*	Total Contribution*	Bldg.	Veh.	Ped.	Total Contribution*	Bldg.	Veh.	Ped.
1	< 2 ci, dispersible	.53	.76	.19	.05	.77	.03	.88	.09
2	≥ 2 ci, dispersible	.36	.85	.08	.07	.04	.84	.09	.07
4	< 2 ci, non-dispersible	.06**	.01	.61	.07	.07	--	.68	.07
5	noble gases	.04	.02	.88	.10	.11	.02	.88	.10
	Weighted Average		.72	.22	.06		.06	.85	.09

*See Table 4-7.

**.31 of LCF's and .27 of GE are due to crew exposure.

The most significant dose pathway shows a strong dependence on accident severity category. In accidents in which no material is released (e.g., Category I for type A packages, etc.), the non-release accident obviously accounts for the entire dose. In loss-of-shield accidents involving non-dispersible materials, the direct exposure dose overshadows the remnant dose. In accidents in which dispersible materials (large, small, and noble gases) are released, however, all three dose pathways--cloudshine, dispersal, and remnant dose--can come into play. Section 1 of Table 4-10 shows the contribution of each of these pathways to latent cancer fatalities and genetic effects for the various severity categories. The second section of Table 4-10 shows the fractional contribution to health effects by severity category for the two major package types. (Note that, from a <u>release</u> point of view, casks and type B packages are treated identically.) The major categories for latent cancer fatalities are those of intermediate severity, where accident rates remain significant. The extremely severe accidents (i.e., Categories VII and VIII), discussed in section 4.6 of this chapter, contribute very little to the expected value of risk.

In sum, the expected value of radiological risk is dominated by dispersal of small-curie quantities of medical-use isotopes shipped by truck in type A packages. Inhalation is the principal dose pathway for latent cancer fatalities and early effects; and direct exposure from nonreleased material, remnant material, and cloudshine is the principal dose pathway for genetic effects.

TABLE 4-10

Expected Value Risk Contribution -
Dispersal Material Dose Pathways by Severity*

Severity Category	LCF**			GE**			Fractional Contribution by Severity			
							Type A Pkg.		Type B Pkg.	
	R*	CS*	I*	R*	CS*	I*	LCF	GE	LCF	GE
I	***	***	***	***	***	***	.02	.50	-	.48
II	8	-	.92	.98	.02	-	.12	.33	-	.31
III	2	-	.98	.87	.13	-	.22	.12	.06	.12
IV	-	-	1.0	-	1.0	-	.49	.02	.19	.05
V	-	-	1.0	-	1.0	-	.10	-	.53	.02
VI	-	-	1.0	-	1.0	-	.04	-	.21	-
VII	-	-	1.0	-	1.0	-	-	-	.02	-
VIII	-	-	1.0	-	1.0	-	-	-	-	-

* R - remnant dose
CS - cloudshine dose
D - dose due to inhalation
LCF - latent cancer fatality
GE - genetic effect

**Type A package assumed. Type B packages have a similar distribution except that the first non-zero severity is III rather than II.

***The entire Category I impact results from the nonrelease accident dose.

In evaluating the information in Tables 4-5 through 4-10, certain additional observations concerning the sensitivity of the calculation can be made. Initially, a review of the routing information in Appendix A reveals that a significant portion of some routes pass through cells which are near the northern border of the grid. Since the prevailing winds are generally from the south, this means that a cloud formed from an accident can affect areas within the city but outside the specific study grid. In order to quantify this effect, comparisons of METRAN outputs with outputs from another dispersion code was made. The results showed that virtually all early effects are confined to the cell of release and that, even for border cells, most of the long-term effects occurred within the grid. Under extreme conditions, an increase of perhaps a factor of two might be expected if the release occurred in a northern border cell and if the wind were southerly.

Several meteorological conditions and times-of-day were evaluated. However, their effect is relatively minor. This results from the fact that most of the long-term effects occur to people in buildings and, although the local densities vary, the total number of people affected does not vary as much. That is to say, people move from one area during the day to another at night. Therefore, the overall number of people in buildings varies by about a factor of 2. Thus, variation of wind speed and direction do not cause order of magnitude changes in long-term health effects. Because early effects are essentially confined to the cell of release, a larger variation with meteorology and time-of-day is observed.

4.5 Decontamination Costs

Extensive contamination of an area as a result of fallout from a cloud of radioactive debris can cause large economic losses to homeowners, businesses, and local, state, or federal agencies. These losses take the form of clean-up costs, evacuation costs, income loss, and perhaps capital outlay for replacement of equipment or raw materials. This is particularly true in an urban area where contamination of even small areas can adversely affect a large number of people.

A previous study[1] has examined the economic impact of contamination from transportation accidents using data from Reference 15. Chapter 6 of this report uses that data, adapted to the urban setting. Figure 4-6 shows the area affected as a function of the amount of material which becomes airborne following the incident. A clean-up level of 0.65 $\mu ci/m^2$ is assumed based on the large-scale decontamination effort which followed the Palomares, Spain nuclear weapon incident.[16]

Although the actual contamination pattern will vary considerably from incident to incident as a function of exact accident location, initial cloud height, etc., some order-of-magnitude estimates of the economic effect can be made. Figure 4-7 shows the curve developed for high-density urban areas, assuming long-lived contaminants. Costs for large releases of short-lived contaminants would be comparable since the driving forces are evacuation and income loss. For smaller quantities, costs for short-lived contaminants would probably be lower than those for long-lived contaminants because areas such as parks, etc. could be condoned off for some period of time.

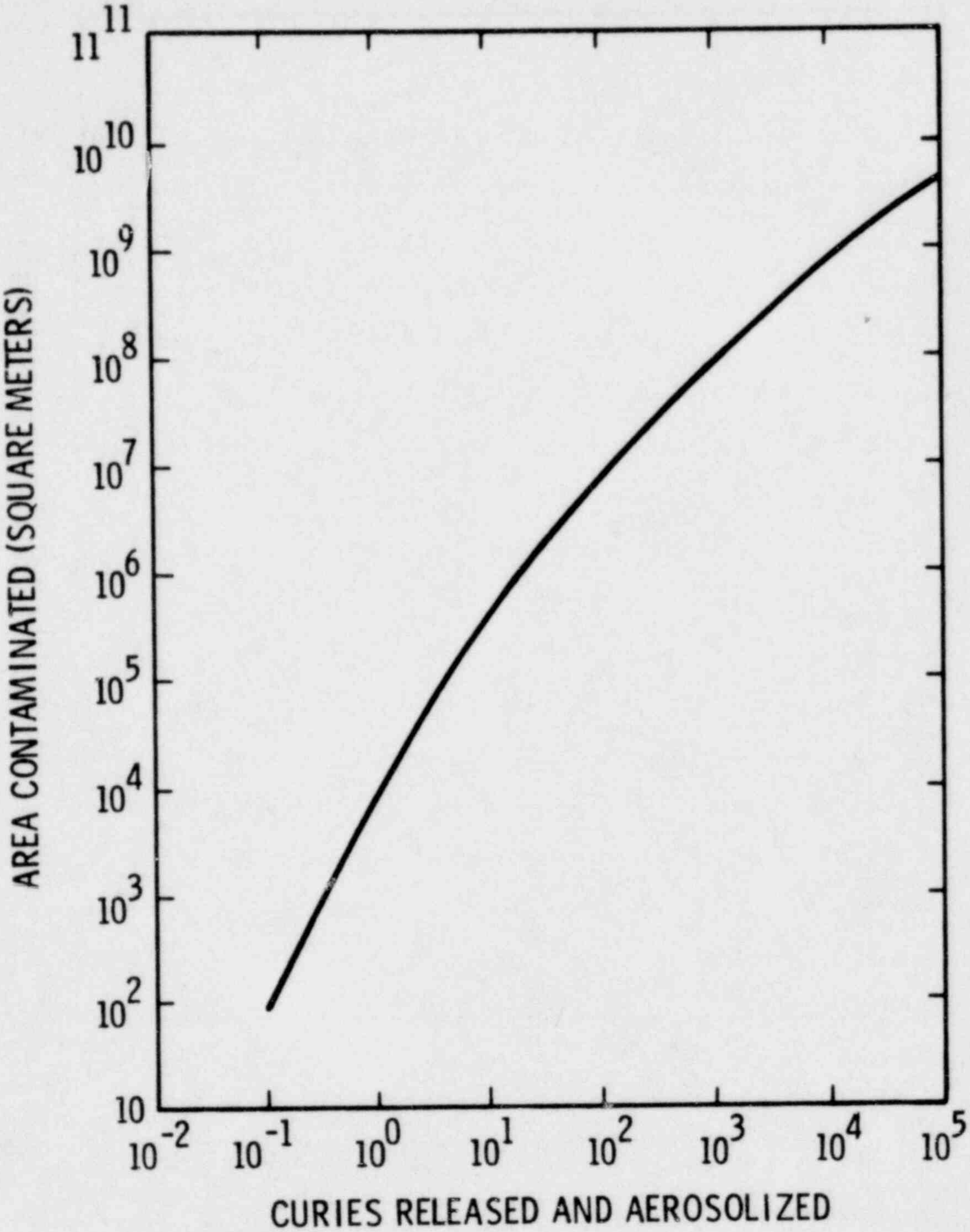

Figure 4-6. Area Contaminated Versus Curies Released and Aerosolized

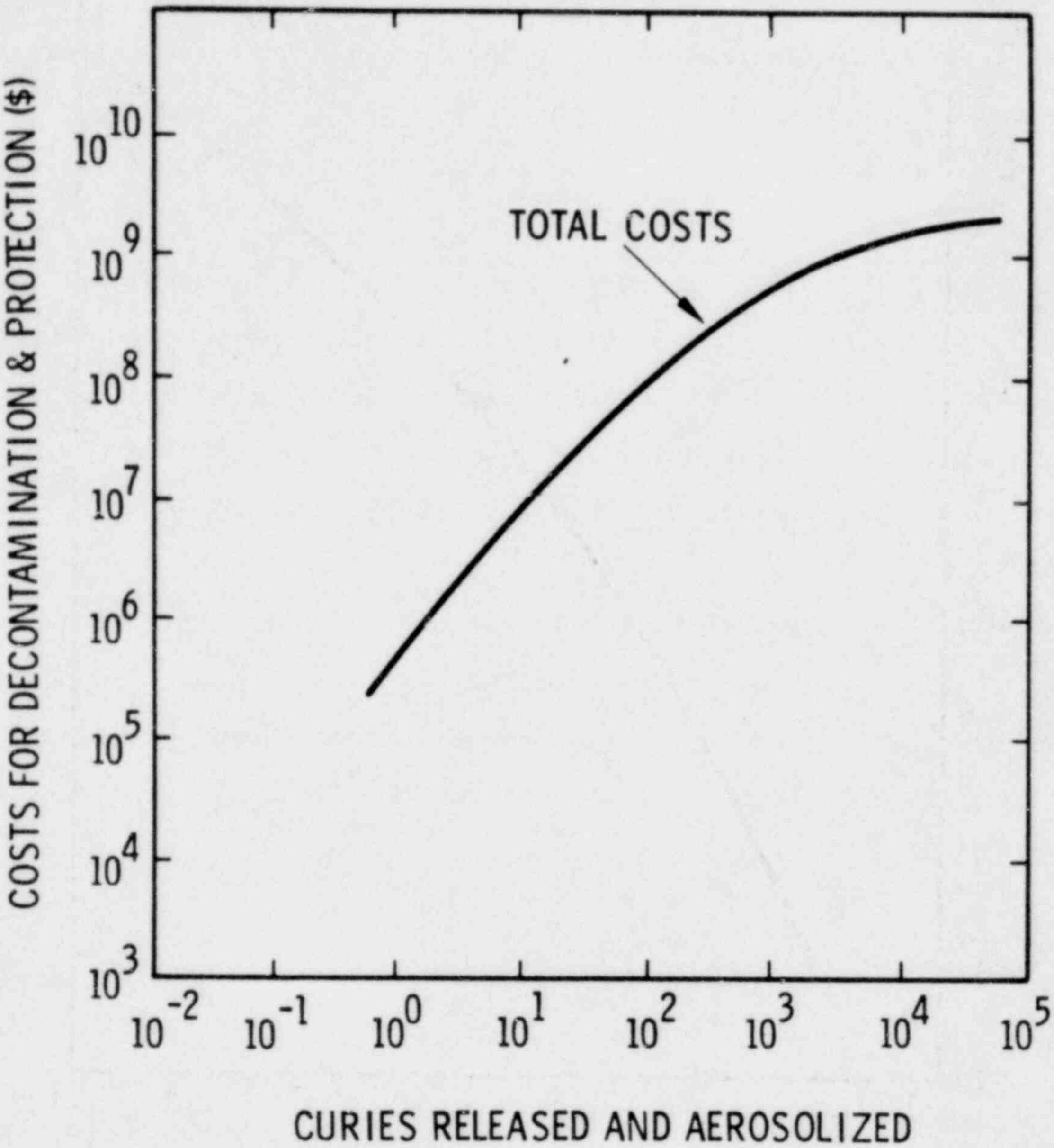

Figure 4-7. Decontamination Costs in Urban Areas

In order to evaluate the impact of the actual shipments, some perspective on the number of dispersible curies shipped is needed. Table 4-11 shows the curie size range for each of the major end-use categories, and whether the isotopes are principally long- or short-lived. The largest dispersible quantity is 3000 curies of long-lived material, available in irradiated reactor fuel. Two items should be noted at this point: (1) contamination effects from from intentional dispersal are addressed in Chapter 6 and are not repeated here, and (2) the cleanup costs associated with restoration of the immediate accident site, including removal and disposal of bulk contaminants (e.g., piles of material or contaminated transport equipment) are not included.

Table 4-11 and Figure 4-7 together show that potential cleanup expenses range as high as several hundred million dollars. Cleanup costs for accidents involving medical-use isotopes range up to $7 million. Costs for accidents involving industrial-use isotopes will be less than $100 thousand, and for major fuel cycle incidents up to $700 million.

TABLE 4-11

Dispersible Curie Size Ranges for Contamination Cost Estimates

End-Use Category	Curie Range	Predominant Half-life Category
Medical	2.2×10^{-5} - 91.	Short
Industrial	1.0×10^{-4} - 0.22	Long
Fuel Cycle	3.5×10^{-6} - 3000	Long
Waste	4.2×10^{-6} - 8.4×10^{-5}	Long

4.6 Low Probability/High Consequence Accidents

The quantification of risk for the product of probability and consequence is only one form of risk analysis used in decision-making. In dealing with potentially high consequences but low probability events, an approach to risk analysis called "mini-max" is also useful.[17] This technique involves the calculation of the consequences of certain events separate from their probability with the thought in mind that at some point the consequences are too severe to tolerate, even at an extremely low probability.

This section considers the consequences of certain high-level releases that might occur.

Several shipments were selected from the actual New York City shipment model specified in Section 7 of Appendix A. However, since these shipments are averaged to some degree, certain other shipments were added to provide an improved mini-max selection. These additional shipments were selected from the Batelle survey[18] and various other sources, and represent shipments that could conceivably have an urban destination (e.g., a large-curie teletherapy source being shipped to a hospital); origin (e.g., a large-curie source being returned by owner for refurbishment); or a trans-shipment/pass-through point (e.g., plutonium being sent overseas by cargo aircraft). The shipments selected for this mini-max analysis are specified in Table 4-12. The first three entries in Table 4-12 are standard shipments evaluated in th risk analysis. The remainder of the entries are these special additions.

TABLE 4-12

Specification of Shipments Used for Mini-Max Risk Analysis

Isotope	Shipment Size (ci)	Physical Form	Brief Description	Shipment Mode	Package Type
Mo-99	91	Dispersible	Radiopharmaceutical Source Material	Truck	B
Co-60	4700	Non-dispersible	Teletherapy Source	Truck	Cask
Spent Fuel	3000* 217,000	Dispersible Non-dispersible	Spent Rx Fuel	Truck	Cask
Plutonium	1.13×10^{6}**	Dispersible	Overseas Fuel	Cargo Air	BPu
Po-210	144	Dispersible	Industrial Source Material	Truck	B
Co-60	315,000	Non-dispersible	Irradiator Source	Truck	Cask

*The description of spent fuel here is based on specific information obtained from Brookhaven National Laboratory concerning actual shipments through New York City. As such, it is significantly smaller than the large shipments discussed in Chapter 6.

**This shipment represents 100 kg of PuO_2 using the reactor-grade mixture discussed in Chapter 6. It is assumed, as discussed in Section 9.2.3 of Appendix A, that only 5% of the released material from a shipment of this size becomes airborne.

The consequence analysis was performed using the METRAN code to evaluate only the consequences of maximum severity accidents. Results for latent cancers, early morbidities, early fatalities, and decontamination cost are presented in Table 4-13. In evaluating these numbers it should be remembered that the annual probability of occurrences is very small, and in some cases zero, since no such shipment may occur in a given year.

4.7 Model Comparison

Because the consequence model developed for this study involves several new ideas, it is important where possible to use results from other proven models in order to validate results obtained using this model. To accomplish this, the CRAC code[19] and METRAN were run using similar source terms and population distributions. The CRAC code, developed for use in analyzing reactor accident consequences, uses a Monte Carlo technique to combine meteorological data for input to a Gaussian dispersion code. It follows the downwind diffusion of the resultant cloud and calculates consequences related to health effects. The output from CRAC takes the form of a mean, a maximum, and a standard deviation for a large number of trials for each of several health effects. The METRAN calculation is different in that it computes a central estimate of consequences for a given release location and windfield.

In spite of these differences, comparison of average values from several METRAN runs can be made with CRAC outputs using the same source term but varied locations and windfields. Table 4-14 shows the results for both codes. In most cases, values agree to within a single CRAC standard deviation, and in all cases the METRAN value is less than the CRAC maximum.

TABLE 4-13

Results of Low Probability/High Consequence Accident Analysis

Isotope	Latent Cancer Fatalities	Early Morbidities	Early Fatalities	Decontamination Costs
Mo-99 (91 ci)	.02	0	0	$\$10^8$
Co-60 (4700 ci)***	.04	0	0	0
Spent Fuel (3000/2.17×10^5 ci)*	10	6	0	$\$7 \times 10^8$
Plutonium (1.13×10^6 ci)**	3964	952	18	$\$2 \times 10^9$
Po-210 (144 ci)	3	8	1	$\$10^7$
Co-60 (315,000 ci)***	4	0	0	0

*3000 dispersible/2.17×10^5 special-form.

**100% released, 5% aerosolized.

***Special form.

TABLE 4-14

Comparison of CRAC and METRAN Results

Material	Quantity Aerosolized (ci)	CRAC* Latent Cancers	CRAC* Early Morbidities	CRAC* Early Fatalities	METRAN Latent Cancers	METRAN Early Morbidities	METRAN Early Fatalities
Spent Fuel	3000	19.2 ±18.6 (79.8)	0	0	9.7	6.4	0
Cs-137	10^{-4}	7.5×10^{-8} $\pm 5.6\text{x}10^{-8}$ ($2.6\text{x}10^{-7}$)	0	0	$6.19\text{x}10^{-9}$	0	0
Mo-99	1.2	$1.44\text{x}10^{-4}$ $\pm 1.1\text{x}10^{-4}$ ($4.85\text{x}10^{-4}$)	0	0	$3.08\text{x}10^{-4}$	0	0
I-131	.0089	$1.3\text{x}10^{-6}$ $\pm 9.4\text{x}10^{-7}$ ($4.4\text{x}10^{-6}$)	0	0	$1.83\text{x}10^{-8}$	0	0
Mo-99	91	$9.99\text{x}10^{-3}$ $\pm 6.9\text{x}10^{-3}$ (.032)	0	0	.0235	0	0
Plutonium	55000	2970 ±2050 (12800)	1440 ±1050 (5360)	543 ±473 (1720)	3964	952	18

*Values given are mean ± standard deviation with maximum parenthesis.

In addition to consequence evaluation, it is of interest to compare the risk results obtained in this study with previous results. The most recent study[1] examined the transportation of all radioactive material shipped in the United States using the same shipment data base[18] used for this study. Two aspects can be compared: absolute numbers and ranking by fractional contributions with various categories.

Initially, one notes that this study predicts a shipment level of roughly 2.8×10^5 per year passing into, out of, or through the New York City area, representing approximately 13% of the nationwide shipping activity predicted in Reference 1. The total expected value of accident risk (expressed by LCF's) from Reference 1 is 4.73×10^{-3} of which 80% (or 3.78×10^{-3}) is assigned to urban areas. It is difficult to say what portion of this value should be assigned to the New York City area. The current study predicts 3.2×10^{-3} LCF for the New York City area alone. Although this may seem high by comparison to the earlier value, it must be considered in light of the New York City area as well as the more detailed urban modeling involved.

The urban density assigned in Reference 1 was 3861 persons/km^2. The urban model described in Appendix A considered people in vehicles, pedestrians, and people in buildings, and predicts more than order-of-magnitude larger density for some portions of the New York area. In addition, New York City is one of a few major interstate transportation hubs, as well as a major export/import center.

When all of these factors are considered, and when the absolute accuracy of the input data is realistically assessed, the actual numerical values of results obtained in this study should not be considered as conflicting with those previously obtained.

As discussed earlier, both absolute values and relative ranking variations between this study and Reference 1 are of interest. Table 4-15 shows the fraction of shipments, curies, and latent cancers from each end-use sector for both reports. Using the number of shipments per year as a benchmark, one notes that by ignoring limited shipments, the NYC traffic is roughly 20% of the nationwide traffic. However, the split among end-use sectors is different. A large fraction of the shipments are medical-use, whereas there are very few waste shipments. In addition, both fuel cycle and industrial shipments are reduced. This reordering is not surprising considering that NYC is not a large industrial center and that there are few fuel cycle facilities (either manufacturing or end-use) in the immediate vicinity.

TABLE 4-15

Comparison of NUREG-0170 and Present Study by End-Use Sector

End-Use Sector	NUREG-1070				Urban Study			
	Packages/Year	f*	LCF	f*	Shipments/Year	f	LCF	f
Medical	9.1×10^5	.61	6.11×10^{-4}	.11	2.27×10^5	.81	2×10^{-3}	.64
Industrial	2.15×10^5	.15	1.6×10^{-3}	.28	3.1×10^4	.11	3.2×10^{-4}	.10
Fuel Cycle	2.04×10^5	.14	1.85×10^{-3}	.33	2.3×10^4	.08	8.6×10^{-4}	.27
Waste	1.52×10^5	.10	6.17×10^{-4}	.11	960	-	—	-
Total	1.48×10^6		5.67×10^{-3}		2.8×10^5		3.2×10^{-3}	

*Values have been renormalized to disregard limited shipments.

Table 4-16 compares the two studies based on package type. When the information is displayed in this fashion, a dramatic difference appears: although the package split is very similar, the impact is skewed away from Type B packages and toward Type A packages and casks. This results from the fact that in Reference 1, 53% of the Type B shipments are special-form, whereas in the present study, 89% of the non-uranium Type B shipments are special-form. (Uranium is eliminated because it is shipped in Type B packages only because of fissile considerations.) Thus, Type B packages would be expected to contribute significantly less in the present study than in NUREG-0170. The increased cask contribution is due to the fact that the spent fuel used to model fuel cycle shipments in NUREG-0170 was released in smaller quantities than the spent fuel used in the urban impact study.

The results of a comparison of the two studies by transport mode are shown in Table 4-17. Although the truck/air split is quite different, most of the risk in both cases is due to the ground link. When these two are lumped together, they are reasonably consistent in predicting over 90% of the risk as resulting from ground transport links.

The dispersibility of the material can be crucial, and there is a significant variation between the shipment analysis in NUREG-0170 and that in the urban study, as shown in Table 4-18. Significant variations occur in cask and Type B package contributions, although the overall breakdown is quite similar.

In both studies, the risk is dominated by intermediate severity (Categories III - VI) releases rather than extremely severe accidents.

TABLE 4-16

Comparison of NUREG-0170 and the Present Study by Package Type

Package Type	NUREG-0170 Packages/Year	f	LCF	f	Urban Study Packages/Year	f	LCF	f
A, Drum	1.4×10^6	.93	2.9×10^{-3}	.51	2.53×10^5	.90	1.9×10^{-3}	.60
B	6.4×10^4	.07	2.8×10^{-3}	.49	2.68×10^4	.10	5.3×10^{-4}	.17
Cask	376	-	1.6×10^{-4}	-	24	-	7.7×10^{-4}	.14

TABLE 4-17

Comparison of NUREG-0170 and the Present Study by Transport Mode

Transport Mode	NUREG-0170 Packages/Year	f	LCF	f	Urban Study Packages/Year	f	LCF	f
Truck	8.69×10^{-5}	.59	4.5×10^{-3}	.79	1.52×10^5	.54	9.3×10^{-4}	.29
Air	--	-	--	-	* 1.1×10^5	.38	2.2×10^{-3}	.68
Air & Truck	5.4×10^5	.36	6.2×10^{-4}	.11				
Ship	2815	-	5.7×10^{-5}	.01	2.31×10^4	.08	9.0×10^{-5}	.03
Rail	6.85×10^4	.05	5.1×10^{-4}	.09	--	-	--	-

*Air freight and passenger air are combined. Virtually all the LCF risk derives from the truck link.

TABLE 4-18

Comparison of NUREG-0170 and the Present Study by Dispersibility

Package Type	Dispersibility	NUREG-0170 Packages/Year	f	LCF	f	Urban Study Packages/Year	f	LCF	f
A, Drum	D	1.3×10^6	.95	2.86×10^{-3}	.99	2.4×10^5	.95	1.7×10^{-3}	.92
	ND	7.36×10^4	.05	4.34×10^{-5}	.01	1.31×10^4	.05	1.6×10^{-4}	.08
B	D	3.0×10^4	.47	2.7×10^{-3}	.96	4000*	.11*	4.1×10^{-4}	.77
	ND	3.4×10^4	.53	1.1×10^{-4}	.04	3520*	.89	1.2×10^{-4}	.23
Cask	D	**	-	$3. \times 10^{-5}$	.19	**	-	7.7×10^{-4}	1.0
	ND	376	-	1.3×10^{-4}	.81	24	-	5.6×10^{-7}	-
Total Dispersible		1.33×10^6	.77	5.4×10^{-3}	.95	2.62×10^5	.94	2.93×10^{-3}	.91
Total Non-dispersible		1.08×0^5	.23	2.8×10^{-4}	.05	1.63×10^4	.06	2.8×10^{-4}	.09

*Uranium in B-fissile packages are not included.

**Spent fuel casks have both dispersible and non-dispersible components. The total number of shipments of this sort are included under cask-D. The LCF's from each type can be distinguished as indicated.

4.8 Summary.

This chapter examines the environmental impact of vehicular accidents from several perspectives. The significant findings are:

1. In terms of expected value of radiological risk due to accidents in urban areas for the specified shipping level, the results are .003 latent cancer fatalities, .007 genetic effects, 7×10^{-4} early morbidities, and 2×10^{-5} early fatalities.
2. The risk is dominated by small, dispersible shipments of medical-use isotopes shipped in type A packages by truck. Spent fuel shipped by truck is also a significant risk factor.
3. People in buildings and vehicles are the largest exposed population groups with inhalation being the significant exposure pathway for latent cancer fatalities and early effects, and direct exposure from nonreleased or remnant material being the significant exposure pathway for genetic effects.
4. Consideration of persons exposed outside the grid might increase certain accident consequences by as much as a factor of two. Variations in meteorology and time-of-day might also cause as much as a factor of two variation in accident consequences.
5. Decontamination, evacuation, and income loss could cost up to $700 million following a major accident. However, most accidents would cost much less, particularly accidents involving small, short-lived medical shipments.

6. Extremely severe accidents have the potential for causing thousands of latent cancers and tens to hundreds of early effects. These accidents have extremely low probabilities, however, and do not contribute significantly to the expected value of risk.

7. Model comparisons for both consequence and risk have been performed and are considered to support the values obtained by METRAN within the accuracy of the input data.

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CHAPTER 5

ENVIRONMENTAL IMPACTS FROM HUMAN ERRORS AND DEVIATIONS FROM QUALITY ASSURANCE PRACTICES

5.1 Introduction

This chapter contains an assessment of the environmental impacts resulting from human errors and deviations from quality assurance practices in the transport of radioactive materials in urban areas. The data sources investigated include the majority of recorded incidents involving radioactive material. The incidents selected for detailed analysis are those which can affect the environmental impacts from transportation. These incidents occur in packaging, labeling, handling, and stowage of radioactive materials. Environmental impacts resulting from vehicular accidents, which may also be influenced by human errors, have been considered in Chapter 4 and will not be analyzed further here. The term quality assurance is used in the present context to mean those aspects which involve possible deviations from procedures or lack of quality control which affect transportation of radioactive materials. These deviations from procedures or human errors may produce environmental impacts in a manner similar to those considered in Chapter 4, i.e., by loss of shielding, loss of containment, or delay of shipments.

Records of actual incidents involving radioactive material transport in urban areas were analyzed to estimate probability rates for the occurrence of incidents involving human errors or deviations from quality assurance on a per shipment basis practices. These "error rates" are used in combination with the radiological consequence code, METRAN, operating in a special mode, to estimate the contribution of these kinds of incidents to the risk of transporting radioactive materials in urban areas.

5.1.2 Human Errors in General

All human performance is characterized by variability. Humans do more things in more ways than any other component of a system, including the most sophisticated computers. However, unlike mechanical or electrical components, humans rarely do anything exactly the same way every time. An act is regarded as an error if it falls outside the limits set on this variability. From a systems point of view, human behavior is considered an error only when it reduces--or has the potential to reduce--system reliability safety or some other success criterion.

The five major categories of human error are:*

1. Failure to perform a task (or part of a task) - an error of omission;
2. Performing a task incorrectly - an error of commission;
3. Performing some task that should not have been performed - an extraneous act;
4. Performing some task out of sequence - a sequential error;
5. Failure to perform a task within the allotted time - a time error.

Any of the above errors can be committed at any time by anyone performing a task or following a set of procedures. Average error rates have been derived for some of these categories in earlier studies.

*This chapter does not address actions such as sabotage or theft, which are deliberate acts, not errors.

For example, the following rates for human errors in nuclear reactor operations excerpted from the Reactor Safety Study:[1]

3×10^{-3} -- General human error of commission, e.g., misreading the label and therefore selecting the wrong switch;

10^{-2} -- General human error of omission when there is no display in the control room of the status of the item omitted, e.g., failure to return the manually operated test valve to the proper configuration after maintenance;

3×10^{-3} -- Errors of omission, where the items being omitted are contained in a procedure rather than at the end as above; and

3×10^{-2} -- Simple arithmetic errors with self-checking but without repetition of the calculation.

These rates are indicative of the range of error rates that one may encounter in any large man-machine system. However, it should be pointed out that most errors are subject to "recovery factors." For example, if an inspector checks the work of a person, he is likely to detect an error, and it can be corrected. Likewise, a misaddressed package will be returned by a trucker who notes, for example, that an address such as "Los Angeles, Texas," is obviously incorrect. In other instances, an incorrectly prepared packing list will be rejected by the packer in the shipping department, because he knows from experience that certain products require special shipping containers, which may be at variance with erroneous instructions on the packing list. However, although most errors are subject to correction through such recovery factors, a certain number will persist through the system and will result in an addition to error statistics.

5.1.3 Human Errors in the Transportation of Radioactive Materials

The environmental impacts associated with the transportation of radioactive materials can be affected by human errors in operations starting from the originator of a shipment to the receiver as shown in Figure 5-1. Operations potentialy affected by human errors in preparation of radioactive materials include procedures to make the material, packaging and labeling of the shipment, and temporary stowage of packages. Additional handling, securing, stowage, and routing operations are often required prior to movement on the transport vehicle. In-transit transfer between carriers can occur during shipment with a repetition of man-machine system operations. In the final phase, a receiver may move the shipment from a depot or airport to the user by procedures and handling which offer the additional possibility for human error.

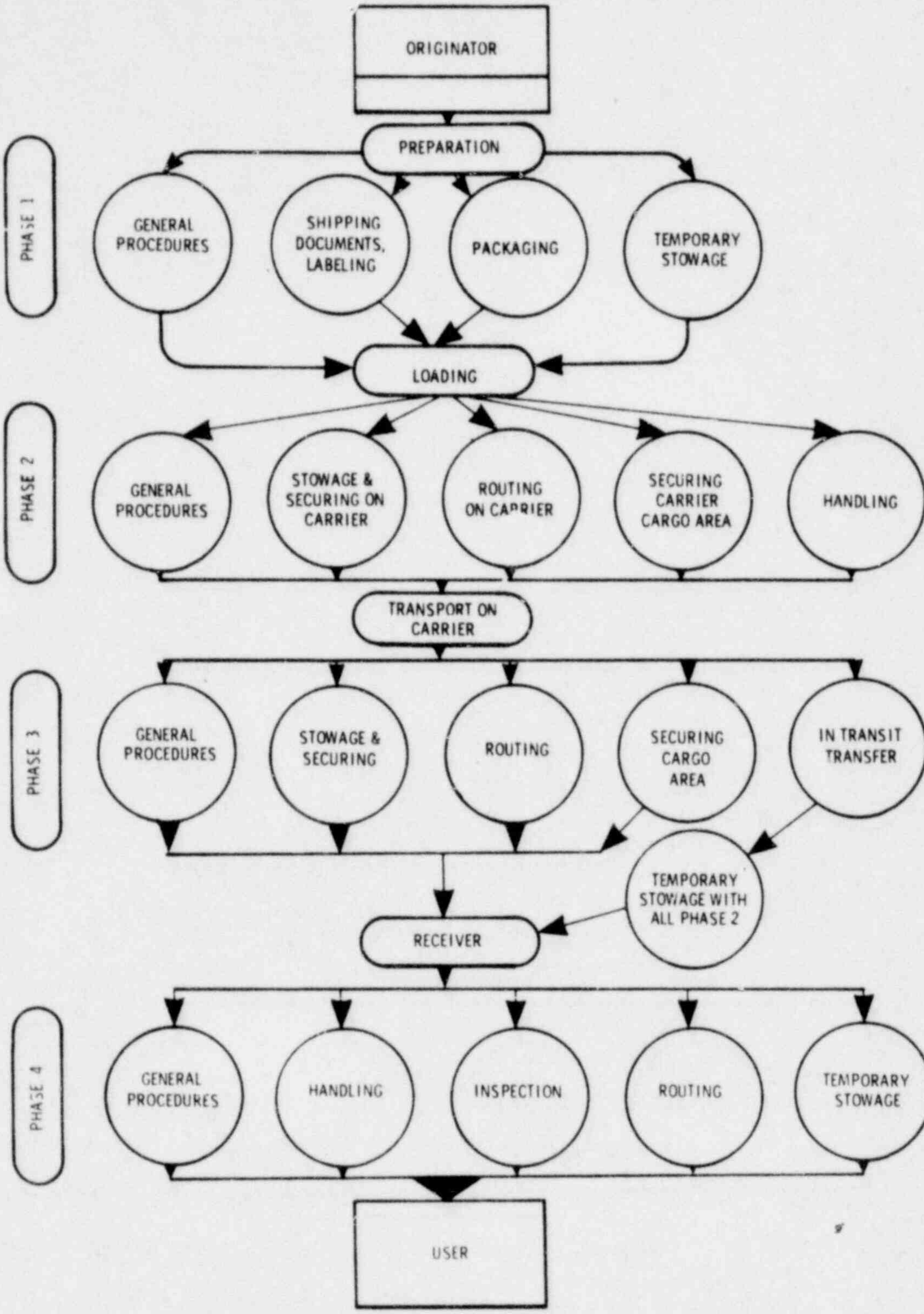

Figure 5-1. Shipment Process for Radioactive Materials where Human Errors May be Involved.

5.1.4 Assessment of the Risk

The general expression for the risk from human error is expressed as expected human health effects for the jth type of shipment of radioactive material, and may be formulated as follows:

$$R_j = PPS_j \; n_j \sum_{i=1}^{8} C_{ij} \; RF_{ij} \; K_{ij}, \qquad (1)$$

where

R_j = risk for the jth shipment, expected latent cancer fatalities/shipment year

PPS_j = number of packages in the shipment

N_j = amount of material per package, curies

C_{ij} = probability per year of a human error of severity class i for shipment type j

RF_{ij} = estimated release fraction for shipment j of severity class i

K_{ij} = number of person-rem per curie (gram)

8 = number of severity classes considered.

Equation 1 shows that the environmental impacts from human errors affecting transport of radioactive materials are dependent on the probability rate C_{ij} for the occurrence of a human error of a given severity and the release fraction RF_{ij}. The concept of release fractions as a function of radioactive material package type and severity class was developed previously[2] and is discussed in Chapter 4 of this report with reference to vehicular accidents in urban areas. Human error rates were not available from previous work but were derived for this study from analysis of available incident data on transport of radioactive material in urban areas.

5.2 Study Approach

Information on the occurrence of human errors and deviations from quality assurance was collected from available governmental, industrial, and commercial sources. In general, only records of incidents reported to the DOT and the NRC were sufficiently detailed to allow categorization of incidents by cause. Shipment data were available for the year 1975 from a previous survey of transport of radioactive materials in the United States.[3] Those incidents involving human errors or deviations from quality assurance were combined with shipment data and used as a basis for the calculation of error rates.

5.2.1 The Data

Sources of data on the number and type of incidents involving radioactive material shipments were developed with the assistance of the Task Group on Transportation of Radioactive Material in Urban Areas. Several members supplied leads within their own organizations, or suggested individuals, agencies, or groups that led to relevant information.

Unfortunately, most potential data sources have not maintained records that could readily be applied to the needs of this study. Most often the data of interest could only be extracted from the actual reports of investigations made by the regulatory agencies. Regulations require that a detailed incident report be submitted to the DOT within 15 days if death, injury, fire, breakage, spillage, or suspected radioactive contamination occurrs as a result of transportation of radioactive materials[4]. Similar reports must be filed with the NRC for any instance in which there is substantial reduction in the effectiveness of any authorized packaging during use.[5] If a local (city, county, state) surveillance agency exists, that agency will usually make and file a report of an incident investigation. False alarms or insignificant investigations are rarely reported to the federal level, but do remain a matter of record at the local level for short periods of time. Reports of incidents thought to be newsworthy are also generally filed and thereby made a part of the record.

5.2.1.1 DOT incident reports

DOT reports on incidents involving transportation of radioactive materials in urban areas are available for the period January 1, 1971 through August 3, 1977. These investigative reports, which describe the events as reported at the time of the incident, are summarized in Appendix I. Of the 251 incidents for that period, only the 153 occurring in urban areas are synopsized. Other information derived from the detailed reports, such as the probable cause of the incidents and transport mode affected, are summarized in Table 1. Human errors or deviations from quality assurance were found to affect 141 of the total 153 incidents. Deviations were about equally divided among air* and surface modes of transport.

The probable cause of the incidents studies include the following:

Stowage - Shipments are blown off carriers, crushed by following vehicles, runover by forklifts, damaged by other freight, fall

*The events charged to air shipments usually occur as a result of actions performed during ground operations before or after flight (a package falls off a loading dock, faulty tie-downs, etc.).

from vehicles, or suffer water damage as a result of insecure or ineffective placement on a carrier or within a terminal area.

Handling - When dropped or punctured, shipments lose package integrity through damage to internal containers or external packaging material.

Packaging - Shipments lose integrity by: failure of external containers; omission of internal padding; defective valve closures; corrosion; improper packaging; welding failures; or drum rupture.

Accidents - Shipments are involved in ground traffic accidents.

Theft/Loss - Radioactive materials are stolen or misdirected in shipment.

Disposal - A damaged radioactive material container is discarded in an unauthorized fashion.

As shown by Table 1, stowage, handling, and packaging account for the bulk of the incidents caused by human errors or deviations from quality assurance. Traffic accidents are not considered in this portion of the study, and theft is considered to involve a purposeful act rather than a human error.

TABLE 1

Department of Transportation Investigative Reports on Radioactive Material Incidents in Urban Areas -- 1971-1977

Incident Cause	No. of Reports	Percent of Total	Human Error/Deviations from Quality Assurance	Percent of Total
Stowage	51	33.3	51	36.2
Handling	39	25.5	39	27.6
Packaging	50	32.7	50	35.5
Vehicular Accident	4	2.6		
Theft/Loss	4	2.6		
Disposal	1	0.7	1	
Unknown	4	2.6		0.7
TOTAL	153		141	

Transport Mode	No. of Reports	Percent of Total
Air	78	51.0
Road	72	47.1
Train	2	1.3
Water	1	0.6
TOTAL	153	

5.2.1.2 NRC Incident Reports

Transportation incident reports for 1975 were provided by the NRC for its five regional offices. Reports pertinent to urban areas are synopsized in Appendix J. As summarized in Table 2, 8 of the 19 incidents in urban areas contained in the NRC files, exclusive of those also reported by the DOT, can be attributed to human errors. As in the case of the incidents reported to the DOT, packaging, handling, and stowage account for the majority of cases involving human errors or deviations from quality assurance.

TABLE 2

Nuclear Regulatory Commission Regional Office Reports of Transportation Related Radioactive Material Incidents in Urban Areas 1975

Incident Cause		Percent of Total	Human Error	Percent of Total
Stowage	2	10.5	2	25.0
Handling	2	10.5	2	25.0
Packaging	3	15.8	3	37.5
Procedure	1	5.3	1	12.5
Theft/Loss	4	21.1	---	
Vehicular Accident	2	10.5	---	
Unknown	5	26.3	---	
TOTAL	19		8	

Additional information was obtained from the NRC for incidents reported by the agreement states for the period July 1976-77. Aspects of these reports are summarized in Table 3. Of the 23 incidents related to transportation, seven involve human errors of the type reflected by previously discussed incident reports.

5.2.1.3 Other Data Sources

Other data sources were investigated in order to obtain a better perspective on the types of human error and general error rates in shipping to be expected.

The Atomic Energy Control Board of Canada reported 61 incidents out of 402,210 radioactive material shipments from 1957-1973. A review of 39 detailed incident summaries for this period shows that 27 were caused by human errors (packaging, stowage, handling, and procedures) of the type described in the U.S. incident reports.

TABLE 3

Nuclear Regulatory Commission Agreement States Reports on Urban Transportation of Radioactive Materials Incidents 1976-1977[6]

Incident Cause		Percent of Total	Human Error/Deviations from Quality Assurance	Percent of Total
Stowage	2	8.7	2	28.6
Handling	4	17.4	4	57.1
Procedure	1	4.4	1	14.3
Theft/Loss	9	39.1	---	
Equipment Failure	1	4.4	---	
Accident	3	13.0	---	
Unknown	3	13.0	---	
TOTAL	23		7	

Information from studies performed in nine states plus New York City, and collated by the Los Alamos Scientific Laboratories,[7] indicate that the same procedures are usually followed at terminals for all types of shipments, including radioactive materials. No special procedures, special stowage, or special loading are consistently applied to radioactive material shipments.

In order to assess incident rates for high volume, general shipments, data were solicited from three major mail-order houses, a major bus company, and the U.S. Postal Service. The reported error rates are listed below.

Mail Order Houses	Error Rate (errors/pkg)
Company A	4.7×10^{-6}
Company B	3.6×10^{-4}
Company C	6.6×10^{-4}
Bus Company	5.0×10^{-3}
U.S. Postal Service	5.7×10^{-5}

These rates reflect all types of errors involved in commercial shipping. They usually include not only cases requiring total replacement of the shipment, but all insurance claim adjustments.

5.2.2 Estimation of Error Rates

Equation 1 requires an error rate as a function of radioactive material shipment type. The data described in the previous sections demonstrate that only a few incidents have occurred involving a small fraction of the hundreds of different isotopes shipped annually. Therefore, a reliable error rate cannot be calculated directly from the data as a function of radioisotope. The DOT and NRC data described in Appendices I and J, however, indicate human errors of the type that may be only dependent on isotope via the magnitude of shipping activity. The package type employed may be a more significant parameter affecting the occcurrences of errors in packaging, handling, and stowage of radioactive materials. Since only a few package types are typically employed, the available data on incidents can be used to estimate errors as a function of packaging.

The error rate per package for package type k may be expressed as:

$$E_k = \frac{\text{total number of packages of type k involved in incidents}}{\text{total number of packages of type k shipped}} \tag{2}$$

and

$$\frac{\sum_{j=1}^{N} B_j f_{jk}}{\sum_{j=1}^{N} n_{jk}}, \tag{3}$$

where

B_j = the number of incidents/year for isotope j

f_{jk} = the fractions of isotope j shipments made in type k packages

n_{jk} = the number of packages of isotope j shipped/year

N = the total number of different isotopes shipped.

Non-zero B_j values were available from the DOT and the NRC incidents reports synopsized in Appendices I and J. Since the incident reports did not identify package type, it was assumed that each incident was apportioned according to the fraction of shipments employing package type k known to be used in shipments of that isotope for the year 1975. That information, as well as 1975 total shipments data for radioactive materials by isotope, can be derived from Reference 3.

The value obtained for the terms in Equation 3 are listed in Table 4. The error rates deduced for the various package types considered are as follows:

Package Type	Error Rate (Errors/Pkg. Shipped)
A	1.1×10^{-5}
B	1.3×10^{-5}
L*	3.4×10^{-5}
LSA*	1.4×10^{-5}
LQ*	2.5×10^{-5}
NS*	2.7×10^{-5}

*L = limited (formerly exempt) packages, LSA = low specific activity packages, LQ = large quantity packages, and NS = package type not specified in BNWL-1972.

TABLE 4

Determination of Error Rates for 1975 DOD and NRC Data

Radio-Nuclide	B_j	F_A	B_{jA}	F_L	B_{jB}	F_L	B_{jL}	F_{LSA}	B_{jLSA}	F_{LQ}	B_{jLQ}	F_{NS}	B_{jNS}
C14	5	$2.8x10^{-4}$	$1.4x10^{-3}$	---	---	$9.9x10^{-1}$	4.9	---	---	---	---	$1.2x10^{-2}$	$6.0x10^{-2}$
CD115M	1	$5.0x10^{-1}$	$4.0x10^{-1}$	$5.0x10^{-1}$	$5.0x10^{-1}$	---	---	---	---	---	---	---	---
CO57	1	$1.8x10^{-4}$	$1.8x10^{-4}$	---	---	$9.1x10^{-1}$	$9.1x10^{-1}$	$8.6x10^{-2}$	$8.6x10^{-2}$	---	---	---	---
CR51	1	$1.8x10^{-3}$	$1.8x10^{-3}$	---	---	---	---	1.0	1.0	---	---	$2.6x10^{-4}$	$2.6x10^{-4}$
H3	3*	$1.9x10^{-4}$	$5.7x10^{-4}$	$9.8x10^{-1}$	2.9	$1.4x10^{-2}$	$4.2x10^{-2}$	$5.9x10^{-3}$	$1.8x10^{-2}$	---	---	$5.7x10^{-4}$	$1.7x10^{-3}$
J125	2*	$2.4x10^{-3}$	$4.8x10^{-3}$	---	---	$5.9x10^{-1}$	1.2	$1.0x10^{-1}$	$2.0x10^{-1}$	---	---	$3.1x10^{-1}$	$6.2x10^{-1}$
I131	6*	$1.9x10^{-2}$	$1.1x10^{-1}$	$9.8x10^{-1}$	5.9	$1.4x10^{-3}$	$8.4x10^{-3}$	$1.2x10^{-3}$	$7.2x10^{-3}$	---	---	$2.7x10^{-4}$	$1.6x10^{-3}$
IR192	2*	$1.9x10^{-3}$	$3.8x10^{-3}$	$1.8x10^{-1}$	$3.6x10^{-1}$	$8.2x10^{-1}$	1.6	---	---	---	---	$2.8x10^{-3}$	$5.6x10^{-3}$
MO99	3*	$1.3x10^{-4}$	$3.9x10^{-4}$	$9.8x10^{-1}$	2.9	$2.5x10^{-2}$	$7.5x10^{-2}$	---	---	---	---	---	---
Pu	2*	$2.6x10^{-2}$	$5.2x10^{-2}$	$8.7x10^{-3}$	$1.7x10^{-2}$	$9.0x10^{-1}$	1.8	---	---	---	---	$7.0x10^{-2}$	$1.4x10^{-1}$
RA226	1	$1.4x10^{-2}$	$1.4x10^{-2}$	$4.4x10^{-1}$	$4.4x10^{-1}$	$1.6x10^{-1}$	$1.6x10^{-1}$	$3.9x10^{-1}$	$3.9x10^{-1}$	---	---	---	---
TC99M	2	$1.2x10^{-2}$	$2.4x10^{-2}$	---	---	---	---	$9.9x10^{-1}$	2.0	---	---	$1.2x10^{-4}$	$2.4x10^{-4}$
TH	2*	---	---	---	---	---	---	$6.0x10^{-1}$	1.2	---	---	$4.0x10^{-1}$	$8.0x10^{-1}$
U	2	$5.8x10^{-1}$	1.2	$5.3x10^{-2}$	$1.1x10^{-1}$	---	---	$1.1x10^{-1}$	$2.1x10^{-1}$	---	---	$2.6x10^{-1}$	$5.3x10^{-1}$
XE133	1	$9.8x10^{-1}$	$9.8x10^{-1}$	---	---	---	---	---	---	---	---	$1.9x10^{-2}$	$1.9x10^{-2}$
Fissile Mat'l	1	$1.8x10^{-1}$	$1.8x10^{-1}$	$8.2x10^{-1}$	$8.2x10^{-1}$	---	---	---	---	---	---	---	---
Non-specified	2	$1.8x10^{-1}$	$3.5x10^{-1}$	---	---	---	---	$8.2x10^{-1}$	1.6	---	---	---	---
Waste Mat'l	3	$7.2x10^{-1}$	2.2	$2.8x10^{-3}$	$8.5x10^{-3}$	$6.1x10^{-1}$	$1.8x10^{-1}$	$1.7x10^{-2}$	$5.1x10^{-2}$	$1.3x10^{-1}$	$3.8x10^{-1}$	$7.3x10^{-2}$	$2.2x10^{-1}$
$\sum_j B_{jk}$ Totals			5.6		14.0		10.9		6.8		0.4		2.4
where $B_{jk} = B_j F_{jk}$													
$\sum_{j=1}^{N} n_{jk}$			$5.2x10^5$		$1.1x10^6$		$3.2x10^5$		$4.8x10^5$		$1.5x10^4$		$8.8x10^4$
$E_k \text{ ship}_k = \dfrac{\sum_j B_{jk}}{\sum_{j=1}^{N} n_{jk}}$			$1.1x10^{-5}$		$1.3x10^{-5}$		$3.4x10^{-5}$		$1.4x10^{-5}$		$2.5x10^{-5}$		$2.7x10^{-5}$

*Includes NRC Data

The error rates obtained are all on the order of 10^{-5}. A small variation in E_k (approximately a factor of 3 or less) is observed for the package types considered.

5.3 Environmental Impacts

The environmental impacts expressed in terms of risk are defined by Equation 1. Important terms affecting risk are the probability of a human error of a certain severity and the expected release fraction. The results of the calculations of risk involving radioactive material shipments for the New York City area are also presented and discussed.

5.3.1 Definition of Fractional Occurrences for Human Errors and Assumed Release Fractions

Equation 1 contains a term, C_{ij}, which represents the probability/year of a human error of severity class i for shipment type j. The error rates developed in the previous sections are only a function of the package type (defined by the shipment information). C_{ij} may therefore be represented as follows:

$$C_{ij} = F_i \times (E \times SPY), \tag{4}$$

where

F_i = fractional occurrence of a human error or deviation from quality assurance of a given severity

E = per package error rate for the occurrence of human errors or deviations from quality assurance for urban transport of radioactive materials

SPY = shipments per year.

In addition,

$$\sum_{i=1}^{8} F_i = 1 . \qquad (5)$$

Eight severity categories were assumed for human errors analogous to the procedure used in Chapter 4 of this report, and in Reference 2 for the analysis of vehicular accidents. The incident data show that approximately 71 percent of reported incidents resulted in no measurable release. F_i was therefore set to equal to .71, and the fractional occurrences for vehicular accidents* were used to scale the remaining F_i. The release fractions, D_{ij}, used in Reference 2 were also employed here** except for the limited category of packaging where any class 2 or greater severity of human error was assumed to result in total release of the contents.

The results of these assumptions and definitions are summarized in Table 5, where derived F_i and assumed D_{ij} are stated. Hypothetical descriptions are also provided for the severity categories used in the analysis.

5.3.2 Risk Results

The radiological consequences model for vehicular accidents, as quantified in the program, METRAN, was used in combination with the probability term shown in Equation 4 to obtain results for the estimated radiological risk from human errors or deviations from quality

*See Reference 2, Table V-3. Fractional occurrences for trucks were employed since the majority of incidents relate to that mode.

**In Reference 2, the more reliable Model II in Table V-8 was used.

TABLE 5

Category	Description	Fractional Occurrences (F_i)	Release Fractions by Package Type (RF_{ij}) L	A	B	LSA	Cask* (Exposure)	Cask* (release)
1	No measurable release	0.710	0	0	0	0	0	0
2	No significant release	0.232	1.0	0.01	0	0.01	0	0
3	For fragile packaging - partial or total release of contents	0.045	1.0	0.1	0.01	0.1	0	.01
4	For fragile packaging - total release of contents	0.010	1.0	1.0	0.1	1.0	0	0.1
5	For sturdy packaging (e.g., type B) total release of contents	0.0018	1.0	1.0	1.0	1.0	0	1.0
6		0.00071	1.0	1.0	1.0	1.0	3.18×10^{-7}	1.0
7		5.5×10^{-5}	1.0	1.0	1.0	1.0	3.18×10^{-5}	1.0
8		9.7×10^{-6}	1.0	1.0	1.0	1.0	3.12×10^{-3}	1.0

*The error rate for large quantity (LQ) is used for casks.

assurance practices affecting transport. The results are expressed as human health effects. The radiological impacts are analyzed with respect to end-use, transportation mode, package type and, time-of-day.

5.3.2.1 Risk Results by End-Use

The risk from human errors or deviations from quality assurance practices affecting the transport of standard shipments* through a typical cell in the New York City grid at three different times-of-day is summarized in Table 6 by end-use. The results shown apply at noon, 4:30 pm, and midnight respectively. The total number of expected annual latent cancer fatalities (LCF's) range from .0094 at noon to .0174 during the afternoon rush. Similarly, the expected annual genetic effects vary from .0022 to .0032 for the same time periods. Medical-use and fuel cycle sources are associated with the bulk of the expected health effects. Medical-use sources are responsible for approximately 80% of the genetic effects and nearly 20% of the LCF's. Fuel cycle sources contribute nearly 10% of the genetic effects and approximately 80% of the LCF's. Large fuel cycle shipments account for 100% of the small number of early effects.

5.3.2.2 Risk Results by Package Type

The risk results by package type are summarized in Table 7. Type A packages are associated with roughly 16% of the LCF's and nearly 90% of the expected annual genetic effects. Casks are related to 80% of the expected annual LCF's and to less than 1% of the genetic effects. Type B packages are associated with approximately 16% of the LCF's and around 10% of the expected annual genetic effects.

*See Appendix A

TABLE 6

Risk Contributions by End-Use

End-Use	Curies/Yr	f	Shipment/Yr	f	LCF	f	Genetic Effects	f	Early Morbid.	f	Early Fatal	f
1200 Hrs.												
Medical	$4.65x10^5$	.12	$2.27x10^5$	.805	$1.79x10^{-3}$	.19	$2.59x10^{-3}$	.84	---		---	
Industrial	$7.20x10^5$	.19	$3.10x10^4$	.11	$7.03x10^{-5}$	.008	$2.51x10^{-4}$	.08	---		---	
Fuel Cycle	$2.61x10^6$	.69	$2.32x10^4$	.08	$7.54x10^{-3}$	.81	$2.69x10^{-4}$	.09	$5.61x10^{-3}$	1.0	---	
Waste	$6.00x10^{-2}$	---	$9.60x10^2$	.003	$1.35x10^{-6}$	----	$9.10x10^{-6}$	---	---		---	
Totals	$3.8x10^6$		$2.8x10^5$		$9.36x10^{-3}$		$3.07x10^{-3}$		$5.61x10^{-3}$		---	
1630 Hrs.												
Medical	$4.65x10^5$	.12	$2.27x10^5$	.805	$3.24x10^{-3}$	.19	$2.72x10^{-3}$	.84	---		---	
Industrial	$7.20x10^5$	.19	$3.10x10^4$	.11	$7.24x10^{-5}$	.004	$2.63x10^{-4}$	.08	---		---	
Fuel Cycle	$2.61x10^6$	.69	$2.32x10^4$	.08	$1.40x10^{-2}$	.80	$2.79x10^{-4}$	.09	$1.19x10^{-2}$	1.0	$3.13x10^{-4}$	1.0
Waste	$6.00x10^{-2}$	---	$9.60x10^2$	.003	$1.35x10^{-6}$	----	$9.10x10^{-6}$		---		---	
Totals	$3.8x10^6$		$2.8x10^5$		$1.74x10^{-2}$		$3.25x10^{-3}$		$1.19x10^{-2}$		$3.13x10^{-4}$	
2400 Hrs.												
Medical	$4.65x10^5$	.12	$2.27x10^5$	.805	$1.60x10^{-3}$	.15	$1.85x10^{-3}$	.82	---		---	
Industrial	$7.20x10^5$	.19	$3.10x10^4$	.11	$4.70x10^{-5}$	.004	$1.82x10^{-4}$	.08	---		---	
Fuel Cycle	$2.61x10^6$	.69	$2.32x10^4$	.08	$8.93x10^{-3}$	.85	$2.06x10^{-4}$	.09	$4.40x10^{-3}$	1.0	$4.20x10^{-4}$	1.0
Waste	$6.00x10^{-2}$	---	$9.60x10^2$	.003	$9.20x10^{-7}$	----	$6.35x10^{-6}$	.003	---		---	
Totals	$3.8x10^6$		$2.8x10^5$		$1.05x10^{-2}$		$2.25x10^{-3}$		$4.40x10^{-3}$		$4.20x10^{-4}$	

TABLE 7

Risk Contributions by Package Type

Package Type	Curies/Yr	f	Shipments/Yr	f	LCF	f	Genetic Effects	f	Early Morbid.	f	Early Fatal	f
1200 Hrs												
A	$2.60x10^5$	.07	$2.54x10^5$	.88	$1.50x10^{-3}$	.16	$2.76x10^{-3}$	.90	---		---	
B	$6.43x10^5$	.17	$2.68x10^4$	.09	$3.53x10^{-4}$	.04	$3.47x10^{-4}$	.10	---		---	
Drum	$2.82x10^5$	.07	$7.60x10^3$	.03	$1.26x10^{-6}$	---	$8.4x10^{-6}$	---	---		---	
Cask	$2.61x10^6$	.69	$1.20x10^1$	---	$7.50x10^{-3}$	.80	$1.8x10^5$	.006	$5.61x10^{-3}$	1.0	---	
Totals	$3.8x10^6$		$2.8x10^5$		$9.36x10^{-3}$		$3.07x10^{-3}$		$5.61x10^{-3}$		---	
1630 Hrs.												
A	$2.60x10^5$	.07	$2.54x10^5$	.88	$2.76x10^{-3}$	.16	$2.91x10^{-3}$	.89	---		---	
B	$6.43x10^5$	.17	$2.68x10^4$	.09	$6.38x10^{-4}$	.04	$3.49x10^{-4}$	.11	---		---	
Drum	$2.82x10^5$	.07	$7.60x10^3$	.03	$1.26x10^{-6}$	---	$8.41x10^{-6}$	.003	---		---	
Cask	$2.61x10^6$	.69	$1.20x10^1$	---	$1.40x10^{-2}$	.80	$2.80x10^{-5}$	.009	$1.19x10^{-2}$	1.0	$3.13x10^{-4}$	1.0
Totals	$3.8x10^6$		$2.8x10^5$		$1.74x10^{-2}$		$3.25x10^{-3}$		$1.19x10^{-2}$		$3.13x10^{-4}$	
2400 Hrs.												
A	$2.60x10^5$	.07	$2.54x10^5$	.88	$1.37x10^{-3}$	.13	$1.96x10^{-3}$	.87	---		---	
B	$6.43x10^5$	.17	$2.68x10^4$	.09	$3.09x10^{-4}$	.03	$2.57x10^{-4}$	.11	---		---	
Drum	$2.82x10^5$	.07	$7.60x10^3$	.03	$8.51x10^{-8}$	---	$5.89x10^{-6}$	.003	---		---	
Cask	$2.61x10^6$	.69	$1.20x10^1$	---	$8.98x10^{-3}$	.85	$1.50x10^{-5}$	.007	$4.40x10^{-3}$	1.0	$4.20x10^{-4}$	1.0
Totals	$3.8x10^6$		$2.8x10^5$		$1.05x10^{-2}$		$2.25x10^{-3}$		$4.40x10^{-3}$		$4.20x10^{-4}$	

5.2.3.2 Risk Results by Transport Mode

The separation of the contributions to risk by transport mode is illustrated in Table 8. Transport by truck and a combination of aircraft and truck produce nearly all ($>$ 99%) of the expected annual health effects. This result is in agreement with the large shipment rates attributable to these transport modes.

5.3.3 Discussion of the Results

The total number of expected annual health effects attributable to human errors and deviations from quality assurance practices is, in general, higher than those found in Chapter 4 for vehicular accidents (.0174 LCF at 4:30 p.m. as compared to the .003 LCF total for vehicular accidents). This result can be inferred by comparing the number of incidents associated with vehicular accidents with the number of incidents involving other human errors as reflected by Table 1.

The large percentage contribution of spent fuel casks to total LCF's is probably an artifact of the assumptions made in the model for casks in lieu of data. No incident reports were found involving spent fuel casks, so no error rate could be calculated for this packaging. As explained earlier, the error rate for large quantity shipments was employed for cask shipping; fractional occurrences were allocated among severity categories analogous to vehicular accidents. This latter assumption is probably conservative for large casks where deviations from quality assurance practices are unlikely to produce material releases which correspond to severe impact and fire conditions. Work is continuing to acquire data and better information for this area of the study.

TABLE 8

Risk Contributions by Transportation Mode

Transport Mode	Curies/Yr	f	Shipments/Yr	f	LCF	f	Genetic Effects	f	Early Morbid.	f	Early Fatal	f
1200 Hrs.												
Air	1.34×10^{4}	.004	8.63×10^{3}	.03	1.12×10^{-5}	.001	1.81×10^{-5}	.006	---		---	
Air+Truck	5.46×10^{5}	.14	9.84×10^{4}	.35	1.50×10^{-3}	.16	1.01×10^{-3}	.33	---		---	
Truck	3.24×10^{6}	.85	1.52×10^{5}	.54	7.84×10^{-3}	.84	1.84×10^{-3}	.60	5.61×10^{-3}	1.0	---	
Ship	4.85×10^{1}	---	2.31×10^{4}	.08	4.00×10^{-5}	.004	2.5×10^{-4}	.08	---		---	
Totals	3.8×10^{6}		2.8×10^{5}		9.36×10^{-3}		3.07×10^{-3}		5.61×10^{-3}		---	
1630 Hrs.												
Air	1.34×10^{4}	.004	8.63×10^{3}	.03	1.79×10^{-5}	.001	1.85×10^{-5}	.006	---		---	
Air+Truck	5.46×10^{5}	.14	9.84×10^{4}	.35	2.94×10^{-3}	.17	1.15×10^{-3}	.35	---		---	
Truck	3.24×10^{6}	.85	1.52×10^{5}	.54	1.43×10^{-2}	.82	1.85×10^{-3}	.57	1.19×10^{-2}	1.0	3.13×10^{-4}	1.0
Ship	4.85×10^{1}	---	2.31×10^{4}	.08	4.50×10^{-5}	.003	2.32×10^{-4}	.07	---		---	
Totals	3.8×10^{6}		2.8×10^{5}		1.74×10^{-2}		3.25×10^{-3}		1.19×10^{-2}		3.13×10^{-4}	1.0
2400 Hrs.												
Air	1.34×10^{4}	.004	8.63×10^{3}	.03	9.2×10^{-6}	.001	1.30×10^{-5}	.006	---		---	
Air+Truck	5.46×10^{5}	.14	9.84×10^{4}	.35	1.40×10^{-3}	.13	7.39×10^{-4}	.33	---		---	
Truck	3.24×10^{6}	.85	1.52×10^{5}	.54	9.14×10^{-3}	.87	1.30×10^{-3}	.58	4.40×10^{-3}	1.0	4.20×10^{-4}	1.0
Ship	4.85×10^{1}	---	2.31×10^{4}	.08	3.10×10^{-5}	.003	1.90×10^{-4}	.08	---		---	
Totals	3.8×10^{6}		2.8×10^{5}		1.05×10^{-2}		2.25×10^{-3}		4.40×10^{-3}		4.20×10^{-4}	1.0

References

1. WASH-1400: Reactor Safety Study

2. NUREG-0170

3. BNWL-1972

4. 49 CFR 171.15

5. 10 CFR 71.61

6. Agreement States Reports 1976-1977

7. Los Alamos Study

CHAPTER 6

SABOTAGE, SECURITY AND SAFEGUARDS IN URBAN TRANSPORT

6.1 Introduction

There is public concern about the safety and physical security of nuclear materials in transit given the continued growth of the nuclear industry. A significant portion of this concern is engendered by the world-wide increase in terrorist activity[1,2,3,4] and the implication that nuclear materials and facilities may become the targets of such attacks.[5,6] Such public concern has led to studies on possible threats to the nuclear industry[7] and evaluations of the environmental impacts of the transportation of nuclear materials.[8,9] This study emphasizes influences on the safe transportation of nuclear materials which may be considered unique to urban area transit. Sabotage and theft are considered in which the presumed intent of the adversary is to inflict public harm (both radiological and economic) either by deliberate dispersal of radioactive material or by causing direct radiation exposure. Various shipments are analyzed from this viewpoint as possible targets. Assuming an attack is carried out which leads to a release of radioactive materials, estimates of the consequences of postulated radioactive releases from these shipments are made using the consequence model developed for the safety portion of this study.

For radioactive material shipments not currently subject to safeguards requirements during transit (e.g., spent fuel, low enriched fresh fuel, radiography sources, radiopharmaceuticals, etc.) this study considers the nature of shipments, the quantity of radioactivity per shipment, its dispersability and toxicity, and the access to the shipment a potential adversary might have in the urban environment

(Sections 6.2 and 6.3). The public consequences of a successful direct sabotage or theft (with ultimate dispersal) are estimated (Section 6.4). The special characteristics of the urban situation are included in the analysis, namely: (1) the high population densities with the attendant heavy vehicular and pedestrian traffic densities, (2) the large diurnal variation in population, numbers of vehicles and pedestrians, and (3) the effect of high rise buildings on the dispersal of radioactive material and the radiation shielding of occupants afforded by such buildings.

For radioactive material shipments subject to safeguards (special nuclear material [SNM], such as plutonium, uranium-233 or uranium enriched to greater than 20 percent in uranium-235), the impact of the urban environment on the function of the safeguards system is examined (Section 6.5). In particular, attention is directed toward the response times, capabilities, and tactics of law enforcement agencies, and how these are affected by the increased population and traffic densities associated with an urban area.

6.2 Potential Modes of Sabotage

If the various types of shipments and related packaging in use in the nuclear industry are considered, it is possible to divide them into two broad classes based upon the degree of resistance they offer to unauthorized penetration. One group includes the large packages (usually casks) that are used for material such as spent-fuel and large shipments of non-fissile radionucildes. Special tools and heavy equipment are normally required to handle and open these packages; therefore, unauthorized penetration will require energy-intensive techniques such as explosives. The second group includes packages which contain low level sources. Many of these packages can be opened with simple hand tools, and in some instances without tools. Because the contained material has low levels of radioactivity, there is no significant hazard to the public. This is discussed further in a later section.

The group of packages which require energy-intensive methods for unauthorized penetration also contain the largest sources of radioactivity and thus provide the greatest potential for public harm. Therefore, it is appropriate to consider further some of the potential methods of sabotage that might be employed against these packages.

6.2.1 Explosives

High explosives are available commercially in a variety of chemical and physical forms. However, for this study, the exact form of the explosive is not of as much interest as the manner in which explosives might be used. For purposes of this study, attacks with high explosive may be categorized as: (1) airblast; (2) contact or breaching charges; (3) shaped charges; and (4) platter charges. Each of these methods is discussed qualitatively in the following paragraphs.

6.2.1.1 Airblast

In a sabotage attack involving air blast, a large high explosive charge would be positioned in close proximity to a package and detonated, employing the resulting air shock wave to disrupt package integrity. The inherent strength and massiveness of large packages such as shipping casks suggest that the charge would have to be extemely large. There are some precedents for terrorist use of relatively large amounts of high explosive, for example, the attack on the University of Wisconsin in 1970 involved approximately 1700 pounds of a fertilizer-fuel oil mixture.[10] Generally, however, terrorist activities have not involved such large amounts of high explosives. Nevertheless, such a mixture is potentially attractive to an adversary because the components can be obtained and the explosive prepared without revealing to suppliers the end purpose.[11]

There are some constraints on the use of airblast that reduce its effectiveness and attractiveness from an adversary's point of view. First, the readily available explosives are bulky. For example, tons of fertilizer-fuel oil mixture probably occupy about 80 cubic feet and would require a truck to transport it. Second, the large quantity of high explosive involved would necessitate that the adversary place the charge and then move to a safe distance before detonation. The airblast overpressures can cause extensive structural damage at considerable distances (hundreds of feet for tons of high explosive) so moving to a safe distance would reduce the adversary's control over the situation. Third, use of airblast would require that the target (truck or rail car) be detained within range of the blast, or that the charge be prepositioned with assurance that the target would pass close by. This would also require that the firing system be sufficiently sophisticated to insure charge detonation at the appropriate time.

In summary, although airblast is relatively straightforward for an adversary to employ, the practical constraints discussed above significantly decrease the likelihood of success if employed against large radioactive material packages.

6.2.1.2 Breaching Charges

In a sabotage attempt involving breaching charges, high explosives would be placed in direct contact with a package and detonated. This is analogous to the use of high explosives to breach large concrete structures.[12] The energy of the charges would be coupled directly into the package, possibly leading to fracture, spallation, and rupture. Here, as with airblast, the strength and massiveness of the large packages would necessitate the use of large charges. It is generally conceded that explosives useful in this type of attack are available "on the street" in quantities such that an adversary could acquire the necessary explosives without contacting government agencies controlling the sale of such material.

With this method of attack it would be necessary for the adversary to gain access to the shipment so that the charge could be placed. With sufficient preparation (knowledge of routes, type of package to be attacked, materials of construction, etc.) a small group could presumably complete such an attack in a short time. Access could be achieved while the truck is parked in a terminal or rest stop. Alternatively, the truck could be hijacked, and then driven to some point where the sabotage would cause the desired public harm. The amount of high explosives required is large enough so that the adversary would have to leave the immediate area before detonation. However, with charges of this size, simple time delay fuses would be sufficient.

As with the airblast attack, there are some inherent constraints which will affect the adversary's success. The weight of high explosives required make it unlikely that "hit and run" tactics would be successful if employed. A potential alternative is the theft or hijacking of the truck, the installation of explosives at some hidden or remote location, followed by detonation and release at some predetermined point. Such a scheme also has inherent constraints. For instance, although mobile, a truck with large radioactive material packages is quite distinct and would be quite obvious unless it were hidden or camouflaged in some manner. Also, movement of hazardous cargo of any type, although it may not be guarded per se, is frequently coordinated with law enforcement agencies. It is unlikely that a theft or hijacking would go undetected for any period of time. Furthermore, a number of the truck systems are over legal roadway weight limits, and, therefore, their routes are carefully planned and coordinated, including in many instances requirements for some type of escort vehicle or movement only during specified hours. All of these serve to deter, or at least complicate, the hijacking of a truck shipment.

Because packages designed for rail shipment are the most massive, the weight of explosive required to breach them is quite large. This negates the possibility of an attack on foot (i.e., the shipment in the rail yard). Similarly, an attempt to place explosives while the train was halted by an obstruction or similar means would appear to require a large, well-trained group. Because the detonation point would be difficult for an adversary to control (dictated more by access than availability of public to intimidate or harm), and the effort to accomplish sabotage is extensive, the use of breaching charges against rail packages appears unattractive for an adversary intent upon maximizing public harm.

Therefore, attacks with breaching charges against truck mounted packages appear possible, however the logistics from an adversary point of view and other constraints reduce its attractiveness. Successful attacks against the very massive rail packages are considered beyond the capabilities of small groups.

6.2.1.3 Shaped Charges

In this type of attack, specially shaped high explosives are placed on the package and detonated. A high temperature, high pressure jet from the shaped charge punches a hole into and through the material. In contrast to breaching charges, which must be placed in direct contact with the target, shaped charges have operational considerations which are a function of the target thickness and the charge weight and geometry.[12,13,14] Shaped charges have been fabricated for the military. Such charges presumably could be obtained by an adversary through theft. Also, with the information available in the open literature it would be possible for a moderately skilled explosives handler to fabricate a rudimentary shaped charge.

As with breaching charges, it would be necessary for the adversary to gain access to the target to place the charge. Again, simple access could be obtained while a truck is parked in a terminal or rest stop. However, use of shaped charges would require that the attacker know the design features of the package in some detail. Thus, although shaped charges can be handled by one or two men, the "hit and run" tactic is not considered a realistic way to initiate a release from a large radioactive material package. As with the breaching charge, hijacking of the truck followed by explosive installation would perhaps be easier for the adversary. Therefore, the constraints (truck visibility, prearranged routes, hazardous cargo escort, etc.) discussed under breaching charges also apply here.

For rail sized packages, an attack with shaped charges is possible since the requisite materials can be carried by men on foot. However, the requirement to modify the target to insure effective charge placement is more prevalent with these larger packages than those that are truck mounted. Therefore, the adversary would have to have some unobserved and uninterrupted time before the target was moved (assuming it is on a siding or in the yard) or a way to control the movement. Here, again, the detonation point is not readily controllable by the adversary without a large effort involving the take-over of significant rail facilities.

Although it appears that an attack using shaped charges might conceivably be attempted against either truck- or rail-mounted shipping packages, the uncertainties facing the adversary materially decrease his likelihood of success.

6.2.1.4 Platter Charges

In this attack, explosives are used to drive a flat steel plate against a target to penetrate it. More correctly stated, the steel plate becomes a blunt projectile under the action of the driving explosive. In such an attack, it is not necessary that the adversary have direct access to the target, although he does have to get into reasonable proximity. Because the plate is simply driven by high explosive, it is not precisely aimable in the sense that an artillery weapon is aimed. However, it has been stated[12] that with practice, a demolitionist can hit a target the size of a 55-gallon drum about 20 percent of the time at a range of 25 yards using a 2 to 6 pound projectile. The massiveness of the large packages discussed earlier suggests that very heavy platters would be required.

Considering the characteristics of platter charges, if an adversary were to attempt an "ambush" type of attack, he would have to know the physical dimensions of the target and have a means to insure that it passed within range of the charge. Because the platter charge is uncontained, any support system for the explosive (truck, for example) would be destroyed on detonation. Therefore, the adversary would have to have a firing system that enables him to operate from a safe distance. The uncertainties in target position and platter performance lead to the conclusion that such attacks would not be attractive to a potential adversary.

6.2.2 Mechanical

There are energy intensive techniques that might be employed in an attempt to penetrate massive packages which may be described as mechanical as opposed to the explosive concepts previously discussed. In most instances, the employment of a mechanical technique requires that an operator be in close proximity, for example, gas cutting torches, powersaws, burn-bars, etc.* Although an adversary might attempt to use such devices, it is clear that for those packages which contain sufficient radioactive material to pose a threat to the public, doing so would put him in considerable danger should he successfully penetrate the package.

*The study assumes that an adversary intent upon dispersal does not have sophisticated radiation-shielded remote handling equipment.

The radiation levels in close proximity to unshielded spent-fuel, for example, can lead to fatal doses in minutes. Thus, it appears that the "hands-on" mechanical techniques would be unattractive to any adversary.

There have also been suggestions that a release from a stolen package could be initiated by deliberate accidents. For example, running it from a highway overpass to drop on the roadway below, crashing it into a bridge or overpass abutment, or some similar accident-like event. Recent tests on the survivability of spent-fuel packages in accident situations have demonstrated that such an approach is unlikely to succeed in releasing radioactive material to the environment.*[15,16,17,18] Other large packages are designed to resist the same accident environments. Another "accident-like" sabotage event that has been suggested is to run a package off a bridge into a river or lake. Because of the impact resistance demonstrated in the referenced crash tests, simply dropping a package into water is unlikely to cause release. Furthermore, packages are designed to withstand at least 25 pounds per square inch external pressure, so submergence into water 50 - 60 feet deep will have no effect. Other analyses suggest that seals will maintain their integrity to even greater depths.

*Initial reports including photographs of test casks are also included in Nuclear News, Vol. 20, Nos. 3, 4, 9 and 14, 1977.

6.2.3 Summary

Possible attacks against large radioactive material packages have been discussed. Some factors affecting the likelihood of success of such attacks have been discussed in a qualitative way, but there has been no attempt to quantify that likelihood. As unlikely as it appears, it is assumed in later sections that an adversary successfully sabotages a radioactive material package. Based on that assumption, consideration is given to the amount and form of the radioactive material that might be released. Consequences of such releases are then estimated using the consequence model.

6.3 Non-Safeguarded Shipments, Potential Adversary Actions and Release

The shipments of radioactive materials that are currently unprotected may be conveniently grouped into seven categories for purposes of this analysis. These are: (1) irradiated or spent fuel from reactors using low enrichment uranium; (2) non-fissile isotopes (large sources); (3) non-fissile isotopes (small sources); (4) less than strategic quantities of SNM; (5) radiopharmaceuticals; (6) low level wastes; and (7) low enriched uranium. These sources are listed in order of decreasing level of curies per package, with the last three being nearly comparable. High level waste is not considered here because there are currently no shipments. Each of the seven groups is considered in further detail below, first in terms of potential adversary actions, next in terms of potential releases, and finally, in terms of estimated consequences (Section 6.4).

6.3.1 Potential Adversary Actions

For each category of shipment, potential adversary actions are discussed considering package contents and package structure.

6.3.1.1 Irradiated (Spent) Fuel

Shipments of spent fuel from light water reactors using low enriched uranium represent the largest single source of radioactivity routinely shipped. A single spent fuel element may contain in excess of 10^6 curies of radioactivity even after 120-150 days cooling time at the reactor site. To an adversary intent upon public harm by dispersal of radioac material or direct radiation exposure, this level of radioactivity may represent an attractive target for sabotage or theft for later dispersal.*

However, the very radioactivity that makes spent fuel an attractive target also serves to enhance shipment resistance to adversary attack. Because of its high radiation level, spent fuel requires considerable shielding for safe handling, which leads to very massive, and therefore durable, shipping containers (casks). These casks weigh from 25 to 100 tons depending upon the number of elements to be carried and the transport mode (truck or rail). Wall construction of these casks may include stainless steel along with lead and/or depleted uranium. Many of the newer designs also include a borated water jacket for shielding purposes.

Access to shipments of spent fuel would be possible for an adversary intent upon sabotage or theft. Truck shipments move on the normal road system and could easily be reached at rest and/or refueling stops by following the truck. Traffic tie-ups could be caused which might stop the shipment and permit access. Of course,

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*Theft with the intent to process spent fuel to recover nuclear weapon material is beyond the scope of this study and is not examined here. In addition, there is disagreement as to the technical capabilities required to accomplish such reprocessing.[5,19]

in the latter instance the adversary runs the risk of having his own progress impeded by traffic. If the shipment travels on urban thoroughfares, normal traffic control could cause stops and give an adversary an opportunity to approach the truck. This could be a possible alternative, especially if theft of the spent fuel were the intent. Rail shipments could be reached enroute if the adversary had knowledge of the route and used vehicles or sabotage to block rail crossings. This is perhaps less likely in urban areas as more overpasses are used to eliminate crossings. Rail cars could be reached in the yards during train make-up, however this would reduce the options available to the adversary since it generally would require him to move on foot. Therefore, truck shipments are considered readily accessible. Rail shipments are also accessible, though with difficulty.

The massiveness of the spent fuel cask, and the type of access available to an adversary, limit to a considerable degree the sabotage schemes that could be employed. The casks are quite invulnerable to small arms fire or small explosive charges. Therefore, even though such items are possessed by dissident groups, a successful attack is highly unlikely. If the intent is dispersal, the potential saboteur is forced to consider other alternatives. Any attempt to open the cask and mechanically disperse the fuel poses significant problems for the adversary. The casks require heavy duty handling equipment (overhead cranes, etc.) and, in some instances, special tools to open the closure system. If the cask were sucessfully opened, the adversary would have to contend with an intense radiation field while attempting to remove fuel from the cask. Thus, successful dispersion by simple mechanical means is unlikely.

With these considerations in mind, it is concluded that an attempt to cause a release with significant public impact will necessarily involve an attack with large explosive charges, as described Section 6.2.1

6.3.1.2 Non-Fissile Isotopes (Large Sources)

Large quantity shipments (10^2-10^6 curies) of non-fissile isotopes present a source of radioactive material that, on a curies per shipment basis, may be only slightly less than that for spent fuel shipments. Therefore, like spent fuel, such shipments may appear to be an attractive target to an adversary intent upon creating public harm by dispersal or direct radiation exposure. Fortunately, the very level of radioactivity that may make it an attractive target for causing public harm serves to enhance resistance to attack. Large quantity shipments require considerable shielding for safe handling. This in turn leads to massive, and therefore durable, shipping containers. Such containers or casks weigh from hundreds of pounds to tens of thousands of pounds depending upon the amount of material to be shipped. These containers are designed to meet Department of Transportation (DOT) and U.S. Nuclear Regulatory Commission (NRC) requirements for type B or large quantity packages. Typically, these containers will have a lead or depleted uranium shield material between an inner and outer layer of stainless steel.

Consideration of the sabotage potential of these containers is quite similar to that for spent fuel casks. Because these containers move in interstate commerce, an adversary intent upon sabotage or theft can conceivably gain access. Truck shipments can be reached in rest/refueling stops or in truck terminal lots.

Traffic tie-ups could be caused which would stop the shipment and permit access. If the container were being moved to an industrial or medical center, normal traffic control could cause stops that would permit an adversary to approach the vehicle. Rail shipments could also be reached if the adversary had knowledge of the shipment routing, although access to rail yards, transfer points, etc. may be more difficult than access to motor freight facilities. For example, a container in a rail yard may well be accessible only on foot.

The increasing massiveness of these containers as the quantity of material increases, and the limited access available to a potential adversary limit his choice of attack schemes. If the intent is dispersal, the adversary has some alternatives, although they all present him with an associated hazard. Any container with shielding thicknesses sufficient for more than a few hundred curies will be invulnerable to small arms fire and attacks involving small amounts of high explosive. If the adversary considers opening the container he faces additional problems. To move the containers or their closures will require some type of mechanical assistance (fork lifts, cranes, etc.) simply because of the weight of the shielding. If the container is opened, the adversary has to contend with an intense radiation field while attempting to remove the contents. Therefore, dispersion by mechanical means will be very difficult to achieve. A deliberate accident to the container (crashing into an abutment, running off an overpass, etc.) is not likely to produce any significant release of material because the containers are designed to retain integrity under just such conditions. Given these factors, the saboteur is forced to consider the use of large explosive charges to cause dispersal. The alternatives available to the adversary here are the high explosive attacks presented in Section 6.2.1.

6.3.1.3 Non-Fissile Isotopes (Small Sources)

Sources for radiography and well-logging have been included in this grouping. Radiography sources are usually a gamma source (Co-60, Cs-137, Ir-192) doubly encapsulated in stainless steel, and when new, the source strength is typically 100 curies or less.[20] Well-logging sources are typically a neutron source (Am-241/Be) of a few tens of curies, combined with a gamma source (Cs-137) of several curies.[20] These sources are also doublecanned in stainless steel. Both types are therefore considered special-form and non-dispersable. Sources of these types do not offer a saboteur a very attractive target. In addition to the fact that the source strength is very low compared to spent fuel or the large non-fissile sources, the design of these sources is such that they will withstand considerable abuse without releasing their contents. Although the shipping containers could be stolen (in some instances they are small enough to be hand-carried and even opened), the radiation field in close proximity to the unshielded source is sufficiently intense that adversaries could not handle the actual sources without some type of shielding and remote handling capability. If an adversary were to steal such sources with the intent to cause public harm by secreting the unshielding source in a public place, the potential effects would be extremely limited.

6.3.1.4 Radiopharmaceuticals

Radiopharmaceuticals are used in the diagnosis and treatment of disease. Because of this use in humans, these products have two principal characteristics that make them unattractive targets for an adversary. First, these isotopes generally have relatively short half-lives (a few hours or less). Second, they are shipped with very little activity in a single package, at most a few curies, generally less.* Theft of, or from, such a shipment is a possibility. However, it would be nearly impossible for an adversary to accumulate sufficient material to create any widespread hazard because the activity in some packages would be decaying while others are collected. Any attempt at dispersal of a single package would lead to sufficient dilution and no significant hazard would be presented to the public.

6.3.1.5 Less Than Strategic Quantities of SNM

Under existing regulations, limited quantities of special nuclear material (uranium enriched to greater than 20 percent U-235, U-233 and plutonium) may be shipped without safeguards. This quantity is 5000 grams determined from the formula: grams = (grams contained U-235) + 2.5 (grams U-233 + grams plutonium).[21] If the shipment were a single isotope then it could be as much as 5 kilograms U-235 or 2 kilograms of U-233 or plutonium. None of these materials presents a significant direct radiation hazard because they are primarily alpha emitters and they have low specific activity compared to other isotopes.[22] Therefore, they do not represent a major early radiological hazard.

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*Source material for radiopharmaceuticals (such as Mo-99) is shipped in significant curie quantities. Multi-curie shipments are considered in Section 6.3.1.2.

As stated earlier, theft of material for purposes of producing or fabricating a nuclear explosive is not addressed in this study. On the other hand, because these materials are alpha emitters they can pose a significant hazard if inhaled, ingested or absorbed through open wounds. For purposes of this investigation, ingestion and absorption are considered highly unlikely and are therefore not considered further. In addition, because plutonium has a much longer effective half-life in the lung (between 200 and 500 days for Pu and 100 days for U) and a much larger specific activity than uranium, only the misuse of plutonium is considered here.

At the present time, plutonium is shipped primarily as plutonium dioxide (powder or pellets) in type B packaging. A recent survey[23] indicates that some 88 percent of the shipments that involve less than 2 kilograms of plutonium are actually quantities less than 100 grams. About 37 percent of the shipments (65 percent of the packages) involve amounts between 1 and 100 grams. The bulk of these shipments are by contract or common carrier. Because these materials move on interstate carriers it must be presumed that a determined adversary could gain access at some point in the transportation cycle, for example, truck terminals, rest stops, etc. Because of the type B packaging, it is unlikely that deliberate accidents (crashes into bridge abutments, etc.) would be successful in releasing any significant quantities of these materials. Likewise, because it may be only part of a shipment inventory, direct explosive attack would not guarantee the adversary a successful dispersal. For an adversary intent upon public harm, the most attractive scheme apears to be theft of one or more packages followed by dispersal at some later time and location.

6.3.1.6 Low Level Wastes

Low level wastes include the by-products of various operations with radioactive materials. Such wastes include soft materials such as contaminated paper, clothing, rags, etc. These soft materials are usually compacted and placed in 55-gallon drums for shipment to disposal sites. An individual drum may weigh several hundred pounds and contain up to a curie of activation and fission products. Liquid wastes, for example contaminated resins and sludges, are dewatered, mixed with solidifying agents (frequently concrete), and placed in 55-gallon drums. These drums usually contain less than 20 curies total activity, although some small fraction may contain as much as 100 curies. The former are shipped as type A packages while the latter are shipped as type B.

In all cases above, when the material is in the transportation sector, it is a solid inside at least a 55-gallon drum. The total activity available in a full shipment of soft waste (approximately 50 drums) is less than 50 curies. To disperse this activity an adversary would have to insure that every drum was opened and the contents volatilized because the activity is bound to the cloth and paper surfaces, either mechanically or chemically. The only realistic path to such volatilization is fire. It is conceivable that a truck loaded with such containers could be set ablaze. But it is unlikely that the adversary could successfully release any significant amount of material for several reasons. First, in any populated area there would be a fire department response to extinguish the blaze. Second, not only would the fire have to be set, but the drums would have to be opened to insure that the contents were exposed to the flames.

For those wastes that have been solidified, an adversary would be forced to consider the use of high explosives to rupture the drums and break up the contents. Certainly in the case of type A shipments, attack with explosives could rupture the drums and cause some breakup of the contents. For type B shipments, this would be more difficult because of the extra packaging, but it could be done. This would necessitate reasonably long access to the vehicle, so that hijacking of a shipment would be required if an adversary selected such material as a target. Considering that a full load of waste represents a source of only 1000-5000 curies total activity--all solidified--such shipments are not attractive targets for an adversary intent upon creating public harm.

6.3.1.7 Low Enriched Uranium

Low enriched uranium (less than 5 percent U-235) is the fuel used in light water power reactors. Typical shipments of fresh fuel may consist of 6 to 12 assemblies in specially designed containers (6 to 12 containers to a semitrailer). The total activity in such a fresh fuel shipment is 0.5 to perhaps 2 curies per container. Because the active material (uranium oxide) is encapsulated in the fuel rods and assemblies which are then packaged, dispersal by mechanical or explosive means would not produce airborne material. Simply scattering the fuel on the ground would not produce any significant radiological hazard because the available activity is so small.

6.3.2 Estimation of Radioactive Material Releases as a Function of Attack Mode

In the preceding section, non-safeguarded shipments were categorized and some possible adversary actions against them identified and discussed. These postulated attacks have been quantified to a limited extent. That is, a particular type of sabotage attack was assumed to be attempted. Based upon that assumption the resources required by the attacker were estimated, e.g., the amount of high explosive required to disrupt large package integrity. After the resources were estimated, the amount of radioactive material that could be released was estimated based upon the damage to the package and contents that could reasonably be expected from the attack.

It must be emphasized that the material releases suggested and summarized here have not been verified experimentally. Although new programs have been proposed to investigate the nature of the releases resulting from explosive attacks, this has not yet been done. Therefore, the considerations presented here are based on engineering judgment and the extrapolation of available data to the present study. With this caveat, the release estimates will be used as the source term to estimate the public consequences of the postulated attack.

6.3.2.1 Iradiated (Spent) Fuel

As indicated earlier, spent fuel shipments represent the largest single radioactive source in the transportation sector, which may make them a target for sabotage. Based upon the massiveness and other design characteristics of these casks it has been concluded that the only realistic way to attack such shipments in order to cause dispersal is with high explosives. Analysis indicates that using air blast as the mechanism to transmit energy to the cask, thousands of pounds of high explosive would have to be detonated in very close proximity to have any chance of disrupting the cask integrity. In such an attack, the most likely result is failure of the cask closure mechanism with some fuel elements being exposed and perhaps even ejected. There is probably no mechanism to create respirable material except for gases and possibly some semivolatiles that might be released from cracked or ruptured elements. In a breaching attack, the analysis indicates that a large amount of high explosive, precisely employed, is necessary to disrupt package integrity. In this attack, because the explosives are in direct contact with the cask, and because of the energy densities involved, coupled with the brittle nature of the spent fuel, it is believed that some radioactive material of respirable size might become airborne. For such an attack, it is considered reasonable to assume that all the fuel elements are at least fractured and that the available volatiles and noble gases will be released.

In the analysis, mechanisms for creating respirable particles were also postulated. For example, with shaped charges, the jet energy may be intensely coupled with the cask and contents, creating respirable material. The release estimated for a platter charge attack is very similar to that for the breaching attack, since the interactions are primarily mechanical and may be intensely coupled. The release fractions are summarized in Section 6.3.2.8.

6.3.2.2 Non-Fissile Isotopes (Large Sources)

The situation with large quantities of non-fissile isotopes is very similar to that for spent fuel. That is, the shipping casks are so inherently massive that the only credible way to cause significant dispersion is with high explosives. Again the analysis indicates that hundreds to thousands of pounds of high explosives are required. However, because the volume occupied by the radioactive material is much smaller in these shipments than for spent fuel (1 to 2 cubic feet compared to 10-12 cubic feet)[24,25] there is a potential for a larger fraction of the material to be released. Perhaps as much as several percent may appear in respirable form, although in this instance it will be a single nuclide and not a mixture of fission products and actinides. The release fractions are summarized in Section 6.3.2.8.

6.3.2.3 Non-Fissile Isotopes (Small Sources)

As indicated earlier, theft of such sources may be possible. If stolen, it is unlikely that an adversary could successfully disperse anything other than the encapsulated source. Any attempt to cut into or grind the capsules would expose the adversary to a hazardous radiation field. Furthermore, because these sources are solids, metals, or inorganic salts, it would be extremely difficult to create particles small enough for airborne dispersal. Attempts to disperse the material explosively could lead to the individual capsules being scattered around, if there were more than one present. However, their small sizes, coupled with their generally metallic nature and double canning, make it quite improbable that there would be any release. The scattered capsules could be a source of direct exposure, although the affected area would be quite small.

6.3.2.4 Radiopharmaceuticals

Radiopharmaceuticals are shipped with so little activity in a single package that they are not considered to be a target for adversary activity. Therefore, no release is estimated for these packages.

6.3.2.5 Less Than Strategic Quantities of SNM

As indicated earlier, the majority of the plutonium shipments in this category involves packages containing 100 grams or less. Furthermore, it was suggested that the attack scheme most likely to produce public harm is theft followed by dispersal. If an adversary steals plutonium with the intent to disperse it, it is assumed that he is sufficiently aware of its properties and toxicity so as to protect himself while handling it. In this analysis, only dispersal which leads to inhalation of the material is considered as the threat. The fraction of any shipment that is respirable (particles less than approximately 10 μm diameter) is a strong function of the method of preparation. Particle size distributions have been reported[9] that have a respirable content from 4 to 40 percent. To be consistent with earlier studies this analysis assumes that approximately 20 percent of the material is respirable. Because the quantities of material involved are easily handled by one or two persons, a number of dispersal mechanisms are conceivable.

One approach is for the adversary to simply scatter the stolen material in an area of heavy foot traffic (transportation terminals for instance) and rely on the movement of people to disperse it. However, even assuming 20 percent respirable material the degree of public hazard from this approach may vary significantly because the amount of material that will become airborne and inhaled is uncertain. Of course, significant surface contamination would result. A second alternative is to introduce the material into the ventilation system of a major public facility (theater, sports arena, etc.). This would certainly cause major contamination clean-up problems, and would expose significant numbers of people, hundreds to tens of thousands, to the respirable component. A third alternative would be explosive dispersal of the stolen material in a heavily populated area (e.g., business district during rush hour or an outdoor sports event.) In the latter instance, a small explosion to scatter material could expose up to a hundred thousand people to the respirable component as well as surface contamination from scattered material. Based upon these considerations, and recognizing the variability in shipments, this analysis will examine the effects of theft and dispersal of 100-1000 grams of plutonium assumed to be 20 percent respirable.

6.3.2.6 Low Level Wastes

As indicated earlier, a shipment of soft waste represents at most a total source of some 50 curies, and requires a very unique set of conditions, probably involving extensive and intensive fire to initiate release. Therefore, these shipments are considered such unlikely targets for adversary action that no release fraction is estimated.

Shipments of solidified waste have a potential for 1000-5000 curies total activity in the shipment. Furthermore, such shipments can conceivably be attacked with high explosives. However, to cause an inhalation hazard the contents must be reduced to particles with diameters less than 10 m. Explosive attack against solid targets like these drums can certainly rupture them and fracture the contents, but it will not pulverize the contents to the extent that a significant airborne release would occur. Such an attack would create a direct radiation hazard and a clean-up problem. For purposes of analysis and comparison with other events, it will be assumed that 1 percent of the contents is released in respirable form and that 50 percent of the contained activity becomes a direct radiation source. This accounts for self-shielding, etc. within large pieces that would probably result from the explosive attack.

6.3.2.7 Low Enriched Uranium

Because the total available activity is so low in fresh fuel it is not considered an attractive target to an adversary intent on public harm. Therefore, no release fraction is estimated.

6.3.2.8 Summary of Estimated Release Fractions

Estimates of the radioactive materials released from the various shipping containers have been made based upon possible sabotage attacks. Table 1 summarizes the estimates for truck mounted spent fuel casks. Because the spent fuel elements contain gases and volatiles, as well as solids, the nature of the potential release will be different from other shipments considered wherein only solids are involved. For the spent fuel it has been conservatively assumed that any fracturing of the elements will permit those gases and semi-volatiles (primarily cesium) that have migrated into the plenum to escape. This assumption is conservative because a fracture some distance away from the plenum may or may not permit the escape of these nuclides. Based upon these estimates, and considering the fact that there is no experimental data specifically designed to elucidate this question, three release fraction combinations are examined to establish the sensitivity of the consequence estimates to the assumptions made regarding release fractions. These three combinations are:

1.* 100% noble gases
    1.6% cesium
    1.0% other radionuclides (solids)**

2. 100% noble gases
    0.8% cesium
    0.2% other radionuclides (solids)**

3. 50% noble gases
    0.4% cesium
    0.1% other radionuclides (solids)**

The release fraction estimates for the other types of shipments are also summarized on Table 1. In these cases the radioactive material is presumed to be shipped in solid form and further that each contains only one isotope. For the estimation of dispersal consequences for the non-fissile isotopes (large sources) two cases will be examined, 2 percent and 0.7 percent of the contents in respirable form. The direct radiation cases will be the same as for the spent fuel. For non-fissile isotopes (small sources) only a

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*Twice the solids release postulated from the attack analysis.

**This excludes cesium. The respirable fraction of cesium in solid compounds has been included with the volatile release.

direct radiation source will be considered in the consequence estimation. No release is postulated for the radiopharmaceuticals or the low enriched uranium. For the remaining two groups the consequences will be estimated for the release fractions indicated on Table 1.

TABLE 1

Summary of Release Fractions

Shipment	Fraction Displaced from Container	Fraction Remaining in Container	Fraction as Scattered Solid Source	Fraction Dispersed as Respirable
Spent Fuel[1,2]	.004 - 1.0[3]	> .99 -.0	.002 - 1.0	.005 - 0
Non-fissile isotope[2] (large source)	.04 - 1.0	.96 -.0	.02 - 1.0	.02 - 0
Non-fissile isotope (small source)	1.0	0.	1.0	-
Radiopharmaceutical	0.	1.0	-	-
Less than Strategic Qty SNM	1.0	0.	0.8	0.2
Low Level Wastes	0.5	0.5	0.5	0.01
Low Enriched Uranium	0.	1.0	-	-

1. Analyses is for truck mounted casks.

2. Release fractions are functions of attack mode; this includes entire range estimated.

3. Refers only to solid material. For spent fuel it is assumed that 100 percent of the noble gases and 0.6% of the total cesium are released from the plenum if the rod is fractured.

6.4 Estimation of the Consequences of an Attack and the Associated Radioactive Material Release

The public consequence of sabotage directed toward radioactive material has several unique aspects. For example, for fixed facilities such as power plants, an actual sabotage act would probably not involve any of the general public. Only the ultimate potential result of such sabotage, the release of radioactive material, could have far-reaching effects. In contrast, for an act of sabotage directed against radioactive material in transit, the dispersal may be deliberately initiated in a public location, for instance a city street, a truck terminal, etc., using large quantities of high explosives. Therefore, the immediate consequences of the explosive attack itself must be considered along with the immediate and long-term radiological consequences related to the release of radioactive material. Where appropriate, such considerations will be taken into account in this analysis, at least in a qualitative manner.

6.4.1 The Consequence Models

The consequences of a release of radioactive material are estimated using the consequence model METRAN developed for the working draft assessment on transport of radionuclides in urban environs. This model is described in appendices to this report, however several features should be mentioned here. METRAN has provisions for considering the details of cloud dispersion on a small geometric scale. This is done using a combination of a three-dimensional layered Gaussian dispersion model and a particle-in-cell dispersion model. Such a treatment is particularly important when small airborne releases in urban areas are considered. METRAN also has provisions for following airborne material concentrations vertically from ground level to a height of 120 meters. The basic calculational elements are cells 1 kilometer square and 30 meters high. The total calculational grid is an area 10 kilometers by 10 kilometers and 120 meters high. As employed here, METRAN is used to estimate the effects of radiation from cloudshine and inhaled radionuclides.* The model explicitly accounts for people in buildings and vehicles as well as pedestrians on the street. The actual population densities are a function of time and location. The release point (any one of the surface cells) and the release time are selected by the analyst. No special protective action is assumed and the population is exposed to the cloud wherever they happen to be at time of cloud passage (i.e., inside buildings, on the street, etc.).

In addition to the estimates made with METRAN, some parallel estimates have been made using CRAC, the consequence model developed for the Reactor Safety Study.[26,27] Although CRAC was not developed with the intent to apply it to the small releases that may be created in the transportation sector, consequence estimates made with CRAC can be useful if interpreted with appropriate regard for the modeling assumptions. For example, CRAC uses time averaged shielding factors to account for population location and does not have the type of detailed population information used in METRAN. Also, CRAC uses a Gaussian diffusion approach to the cloud dispersion problem and,

*The model is being expanded to include direct exposure due to radiation from residual material scattered at the site of the attack. Parallel studies with the consequence model from the Reactor Safety Study indicate that for the larger dispersal release considered here, the contributions to public consequences from exposure to residual material will be minimal.

therefore, lacks sufficient detail close to the release point to examine street canyon effects on cloud progression. On the other hand, CRAC is not restricted to considering a 100-square kilometer grid, but can be used to follow cloud progression out to any selected distance. CRAC also can be used to accumulate results for many different accident or sabotage times throughout a calendar year and thereby obtain mean values and distributions of the estimated consequences over a variety of meteorological conditions. In this particular study, the results using METRAN are consistent with those obtained using CRAC.

With the preceding considerations in mind concerning the range of consequences and the computational tools, the consequence estimates for each of the various classes of shipments for which dispersal is considered realistic are presented in Sections 6.4.2 through 6.4.5.

6.4.2 Irradiated (Spent) Fuel

As established in the earlier discussions, any realistic attack against spent fuel shipments can be expected to involve significant quantities of high explosives. Likewise, if an adversary is intent upon public harm it can be expected that any such attack will take place in densely-populated areas. It therefore becomes appropriate to consider the nonradiological effects of such an attack along with the radiological effects.

6.4.2.1 Consequences of the Use of High Explosives

There are two principal mechanisms for creating damage and causing public consequences using large amounts of high explosive.

One is the air shock or blast wave which propagates radially outward from the blast center. The second is the high-velocity debris created by the interaction of the explosive or the shock wave with surrounding structures. Assuming, for this discussion, that an attack on a spent fuel cask may involve several thousand pounds of explosive, two types of consequences must be considered: First, blast damage to surrounding structures. The blast overpressure associated with the detonation of tons of high explosive is shown as a function of distance in Figure 1.* It may be noted that overpressures greater than 1 psi can be expected to distances on the order of 600 feet (approximately 180 meters). Based upon observed blast effects,[30] windows will be broken and shattered to such distances, buildings of cinder block construction will be damaged at distances of 200-300 feet, and reinforced concrete structures will experience damage at 100-200 feet. It is nearly impossible to estimate the casualties attributable to collapsing structures, flying debris, etc., but at the population densities typical of a hyper-urban environment the number of casualties will be significant. For instance, at the evening rush hour (4:30 p.m.) in one calculational cell of the grid, used as the example for this generic environmental assessment, there will be on the average, about 17,000 people within a 600-ft. radius of any given point. Other locations will have comparable numbers, although exact numbers are location and time dependent. All of these people will be exposed to the effects of the detonation of high explosive. Second, direct effects of the blast blast wave on an exposed populace.

*Adapted from data in references 28 and 29.

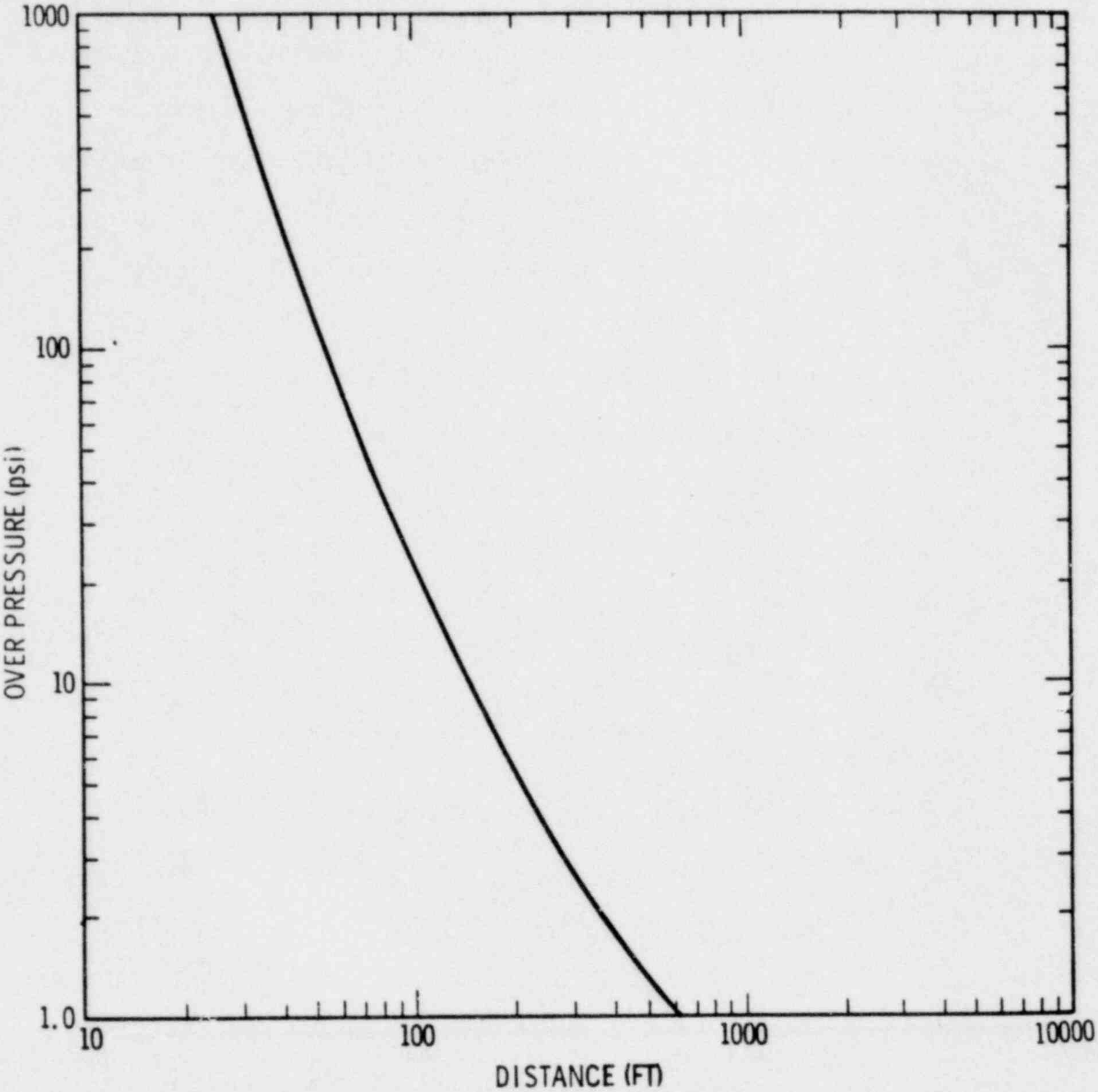

Figure 1. Blast Overpressure from Tons of High Explosive as Function of Distance from Detonation Point

Glasstone[30] reports that there is a 0.99 probability of fatality for people exposed to blast overpressures of 55-65 psi. Assuming that an attack takes place at an intersection, and considering only those people in vehicles and the pedestrians, it is estimated that for the cell at rush hour some 140-150 fatalities may result from direct overpressure alone. Again, other cells give comparable results.

These rather simple illustrations strongly suggest that the immediate non-radiological effects of a sabotage attack in a densely populated area may be as significant or more significant than the radiological effects. As will be shown later, the estimates here (hundreds of fatalities) are comparable t and in some instances exceed the estimates of fatalities predicted to result from the radiological effects of the release, using the METRAN model.

6.4.2.2 Consequences of the Radioactive Material Release - METRAN Estimates for Dispersed Material

The METRAN model has been used to examine the three releases from a spent fuel cask summarized in Section 6.3.2.8.* The spent fuel radionuclide inventory was generated using the fuel burn-up code ORIGEN[31] assuming light water reactor fuel with 33,000 MWd/MTHM burn-up at 40 kw/kg power density and 150 days cooling. The truck mounted cask is assumed to contain radionuclides equivalent to 1.4 MTHM charged to the reactor. The resultant cask inventory is shown on Table 2. Consequence estimates were generated for releases

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*Considerable data were also generated for a fourth case that was used during model development and check out. It is included in these discussions.

occurring in four different cells of the grid, at three times and for a midblock street location. The calculation conditions are shown on Table 3. This calculational approach provides 12 separate consequence estimates for each assumed release. An example of one set is given in Table 4. Because of the limited areal extent of the METRAN grid, the total population at risk is a strong function of the location of the release point, the weather (especilly wind direction), and the time of day. Therefore, it is not appropriate to simply average all the estimates together to generate mean values. It is appropriate however, to average the consequence estimates for a release in a given cell at different times to obtain an average for each release location. Such averages are presented in Table 5 for the spent fuel cask releases.

TABLE 2

Spent Fuel Cask Radionuclide Inventory

1.4 MTHM Charge to Reactor (3 Elements)
33000 MWd/MTHM Burn-up at 40 kw/kg
150 Days Cooling

Radionuclide	Curies
Co-58	3.084×10^3
Kr-85	1.284×10^4
Sr-89	1.746×10^5
Sr-90	1.064×10^5
Y-90	1.065×10^5
Y-91	2.89×10^5
Zr-95	5.083×10^5
Nb-95	9.468×10^5
Ru-103	1.812×10^5
Ru-106	5.803×10^5
Te-127	8.848×10^3
Te-127M	9.033×10^3
Te-129	3.730×10^3
Te-129M	5.874×10^3
Cs-134	3.103×10^5
Cs-137	1.464×10^5
Ce-141	1.008×10^5
Ce-144	1.215×10^6
Pr-143	1.144×10^3
Pu-238	3.641×10^3
Pu-241	1.415×10^5
Cu-242	1.144×10^3
Cu-244	2.851×10^3

*Radionuclides with significant health effects based upon Reactor Safety Study.[27]

TABLE 3

Summary of METRAN Case Locations

1. Cell of Release	A--Expressway
	B--Industrial Area
	C--High Population Density
	D--High Population Density
2. Time of Release	Noon
	Evening Rush Hour
	Midnight
3. Location	Midblock
4. Population Density	Typical of Hyper-Urban Environs (varies with time and location
	Cell A--26,000 to 52,000/km^2
	Cell B--24,000 to 46,000/km^2
	Cell C--50,000 to 77,000/km^2
	Cell D--35,000 to 38,000/km^2

TABLE 4

METRAN Consequence Estimates--Case 1--Spent Fuel[1]

Cell of Release[2]	Time	Location[3]	Early[4,5] Fatalities	Early[4] Morbidities	Latent Cancer[4] Fatalities
A	1200	MB	4	500	160
	1630	MB	23	670	320
	2400	MB	13	520	300
B	1200	MB	6	1500	550
	1630	MB	44	500	300
	2400	MB	29	1100	490
C	1200	MB	11	1000	530
	1630	MB	10	1500	660
	2400	MB	16	760	440
D	1200	MB	17	580	680
	1630	MB	7	170	330
	2400	MB	25	2400	910

---

1. Assumed release from a 3 element cask: 100% noble gas; 1.6% cesium; 1% solids as respirable material. This is the largest release considered from a truck-mounted cask, and is at least twice the solids release fraction postulated in the attack analysis.

2. See Table 3.

3. MB--Midblock.

4. Early Fatalities occur within one year after exposure to the radioactive material. Early Morbidities are illnesses appearing within weeks after exposure. Latent Cancer Fatalities occur over any time subsequent to the exposure as a result of the initial exposure, i.e., 600 latent cancers would represent an average of tens of cancers per year in the population group exposed.

5. These are fatalities from the radiological effects of the release. Blast effects from high explosives sufficient to breach a cask could cause approximately 150 fatalities. (See Section 6.4.2.1.)

TABLE 5

Consequence Estimates--Average for 3 Release Times--
Releases from Spent Fuel

	Cell of Release	Avg. Number of Early Fatalities[5,6]	Avg. Number of Early Morbidities[5]	Avg. Number of Latent Cancer Fatalities[5]
Case 1[1]	A	13	560	260
	B	26	1000	450
	C	12	1100	540
	D	17	1000	640
Case 2[2]	A	13	520	260
	B	15	860	450
	C	7	1100	540
	D	14	970	630
Case 3[3]	A	4	40	270
	B	6	130	90
	C	3	60	100
	D	4	45	100
Case 4[4]	A	1	14	26
	B	2	30	45
	C	1	13	50
	D	1	23	52

---

1. Assumed release from a 3-element cask: 100% noble gases; 1.6% cesium; 1% solids as respirable material. At least twice the solids release fraction postulated in the attack analysis.

2. Assumed release from a 3-element cask: 100% noble gases; 1.0% cesium; 1% solids as respirable material.

3. Assumed release from a 3-element cask: 100% noble gases; 0.8% cesium; 0.2% solids as respirable material.

4. Assumed release from a 3-element cask: 50% noble gases; 0.4% cesium; 0.1% solids as respirable material.

5. See Footnote 4, Table 4.

6. See Footnote 5, Table 4.

The magnitude of the averaged consequence estimates (early fatalities, early morbidities and latent cancer fatalities) do not show any consistent correlation with the grid location of the release. The extent of geographic area affected is not dominant because the population density, and thus the total population exposed, is also a strong function of not only location but time of day. Also, for any given cell of release and street location the estimates clearly show the influence of population density variations and direction of cloud travel as well as time of day. For example, in Table 4, cell C, while the cloud from a noontime release moves primarily north and slightly east, the increase in consequence estimates during the evening rush hour reflects the increase in the number of people on the streets as pedestrians and in vehicles in the area over which the cloud travels. In addition, the lower consequence estimate at midnight for a cell C release reflects the absence of people in a business district (area northeast of cell C) during the nighttime hours, and the fact that a portion of the cloud moves across locations where there are no people. (The direction of cloud travel and areas affected by the release are discussed further in Section 6.4.6.)

It should also be noted that relatively minor changes in population location can have a pronounced effect upon METRAN estimates of early effects. This is due to the fact that METRAN employs a threshold early health effects model; therefore changes in where people are can put significant numbers of people above or below a particular dose threshold.

The average consequence estimates for the four releases are shown in Table 6, when the release occurs in cell B, or near the grid center. The data simply indicate the relationship of consequences to release magnitude. It might be expected that the estimates for Case 3 would just be half of those for Case 4 since the only change is reduction of the source term, and thus the exposure dose, by one-half. The estimates of consequence do not decline by 1/2 because dose response is non-linear and because of the threshold effects just discussed. In this instance, a change in source term magnitude may or may not have a major impact upon the estimates, depending upon the number of persons receiving doses at or near a threshold. Also, in the computational scheme the population dose producing early casualties reduces the population dose available to induce latent cancers. In comparing Cases 1 and 2, the influence of the amount of cesium released is observable. The most pronounced effect is the increased number of early morbidities.

TABLE 6

Average Consequence Estimate Comparison--Cell B--
Releases from Spent Fuel

Case[1]	Early Fatalities[2,3]	Early Morbidities[2]	Latent Cancer Fatalities[2]
1	26	1000	[illegible]
2	15	860	450
3	6	130	93
4	2	30	45

1. See Footnotes 1-4, Table 5.
2. See Footnote 4, Table 4.
3. See Footnote 5, Table 4.

In Table 7, the METRAN estimates for a release in cell B are compared with the estimates from a CRAC calculation for a release at the grid center and for the same area. (The CRAC estimates made in support of this work are described in Section 6.4.2.3.) It can be noted that, generally speaking, there is agreement between the two calculational techniques. The larger estimates of early effects by METRAN are expected for three reasons: (1) METRAN is designed to handle the close-in meteorology with finer resolution than CRAC; (2) because METRAN is specifically designed for transportation accident conditions, it diffuses a "cold cloud," that is, the release cloud has no thermal bouyancy, and therefore, a large portion of the radioactive material stays near the ground where the people are; and (3) the lower boundary of the METRAN grid is "totally absorbing," which tends to keep the centroid of the release cloud low. In contrast, CRAC has provisions for including a thermal source in the cloud which takes into account the effects of high explosives in lofting the material and thus reducing the concentrations. When CRAC is run without a thermal source in the cloud, the estimates of early effects rise. The agreement in latent cancer fatality estimates is considered excellent, although the mean values predicted by CRAC are lower. This is also expected because the population density is slightly lower and the release cloud is more diffuse. The peak latent cancer fatality estimate with CRAC is greater than those from the limited number of METRAN runs.

TABLE 7

Average METRAN Consequence Estimate Comparison with CRAC Mean Estimate[1]

Case[2]		Early Fatalities[3,4]	Early Morbidities[3]	Latent Cancer Fatalities[3]
1	METRAN	26/44	1000/1500	450/550
	CRAC	4/61	160/1600	260/1200
2	METRAN	15/37	860/1300	450/550
	CRAC	4/60	160/1600	260/1200
3	METRAN	6/9	130/170	93/100
	CRAC	-	-	46/220
4	METRAN	2/3	30/63	45/52
	CRAC	-	-	21/110

1. CRAC calculation limited to same 10 x 10 km area assuming a release at center and including only initial exposure, i.e., direct cloudshine and 1-day exposure to ground contamination plus radionuclides inhaled during cloud passage. Second number is maximum estimate occurring during calculation for either code.

2. See Footnotes 1-4, Table 5.

3. See Footnote 4, Table 4.

4. See Footnote 5, Table 4.

All of the consequence estimates were made with the population "in-place": that is, no attempt was made to model or account for evacuation to avoid exposure. This was based on the fact that evacuation may not be possible in all instances. Effective evacuation could serve to reduce the estimated consequences in some cases.

In summary, for a postulated release from a truck mounted spent fuel cask of 100% of the noble gases, 1.6% of the cesium and 1% of the remaining radionuclides, (this is at least a factor of 2 greater than the solids release fraction postulated from the attack analysis) tens of early fatalities may be expected, hundreds to approximately a thousand early morbidities, and hundreds of latent fatalities. The number of casualties associated directly with the use of high explosives in the attack will be comparable and perhaps greater than those due to the release of radioactive material.

6.4.2.3 Consequences of the Radioactive Material Release - CRAC Estimates

The consequence model of the Reactor Safety Study,[26,27] CRAC, was also used to examine the postulated release from spent fuel casks. CRAC was used for several reasons: (1) there is considerable experience available in the use of this model; (2) it allows consequences to be estimated out to great distances from the release point; and (3) parameters may be varied in the model to explore the effects of radiation exposure pathways.

In this particular analysis, the release is centered on the METRAN grid, and the population distribution is based upon the METRAN data for afternoon building occupancy. For radial distances beyond the METRAN grid, the detailed population distribution employed is equivalent to approximately 42,000 people per square mile out to 10 miles, 10,000 people per square mile between 10 and 30 miles, 1000 people per square mile between 30 and 55 miles, and 100 people per square mile beyond 55 miles. The detailed distribution accounts for the fact that there is no population in the seaward area by setting the population equal to zero in certain segments. The total population thus included closely approximates the actual population within 500 miles of the assumed release point.

CRAC operates basically on a radial computational mesh. The circular area is centered at the release point and divided into 16 segments of 22-1/2°. Each segment has 34 radial intervals. For this study the interval spacing is 0.5 km out to 10 km from the release point (to approximate METRAN); then the interval width expands. The outer radius of each interval is shown on Table 8. In this analysis, a release cloud is permitted to traverse each segment (16 segments for 91 sequences of weather conditions (91 trials), representative of weather near the release point. The mean values of consequences then reported represent the mean from 1456 separate trials.

TABLE 8

CRAC Estimate - Radial Intervals

Interval No.	Radius (KM)	Radius (mi)
1	0.5	0.31
2	1.0	0.62
3	1.5	0.94
4	2.0	1.25
5	2.5	1.56
6	3.0	1.88
7	3.5	2.19
8	4.0	2.5
9	4.5	2.8
10	5.0	3.10
11	5.5	3.44
12	6.0	3.75
13	7.0	4.38
14	7.5	4.69
15	11.2	7.0
16	16.0	10.0
17	24.0	15.
18	32.0	26.
19	40.0	25
20	48.0	30.
21	56.0	35.
22	64.0	40.
23	72.0	45.
24	80.0	50.
25	88.0	55.
26	96.0	60.
27	104.	65.
28	112.	70.
29	136.	85.
30	160.	100.
31	240.	150.
32	320.	200.
33	500.	350.
34	800.	500.

In the analysis, each of the four releases mentioned earlier was examined under several conditions. First, the population was limited to the area (100 square kilometers) covered by the METRAN grid, and the radiation dose was restricted to that from cloudshine during cloud passage, one day exposure due to radionuclides deposited on the ground and buildings, and from radionuclides inhaled during cloud passage. It therefore "duplicates" the METRAN analysis except for the inclusion of direct radiation from surface contamination. The results are shown on Table 9. These are also the values shown in the comparison of CRAC and METRAN results (Table 7). Second, the population base was expanded to include people out to 500 miles, as described earlier, with the other conditions as described above. Results for the two larger releases are shown in Table 9.

Several observations are appropriate concerning these results. Considering only the effects of early exposure, more than 70% of the latent cancer deaths will result from exposure close to the release (less than 10 km). As indicated earlier, METRAN estimates do not include exposure to deposited material. A CRAC estimate was made considering only the inhaled material (Table 9). The results indicate that for these releases (limiting the dose from surface contamination to one day) the dose from inhaled radionuclides clearly dominates the latent effects ($\sim$ 98%).

TABLE 9

CRAC Consequence Estimates for Releases from Spent Fuel Casks

Case[1]	Early Fatalities[2,3,4] Mean/Peak	Early Morbidities[2,3] Mean/Peak	Latent Cancer Fatalities[3] Mean/Peak
1. Population Limited to METRAN Grid			
1	4/61	160/1600	260/1200
2	4/60	160/1600	260/1200
3	-	-	46/220
4	-	-	21/110
2. Population Present to 500 Miles			
1	4/61	160/1600	350/1400
2	4/60	160/1600	350/1300
1[5]	4/60	160/1600	350/1300

[1] See Footnotes 1-4, Table 5.

[2] Mean radius for early fatalities is 55 meters, peak 500 meters. Mean radius for morbidities is 104 meters, peak 500 meters.

[3] See Footnote 4, Table 4.

[4] See Footnote 5, Table 5.

[5] Only pathway is from inhaled radionuclides.

An alternate view of the spatial distribution of latent cancer fatalities is shown in Figure 2, where cumulative latent fatalities are plotted against radial distance from the release point. The change in slope in the vicinity of 10 kilometers indicates that, as the population distribution has been modeled here, and using the CRAC model, the majority of the latent fatalities will occur in the population near the release point. This is further illustrated by Figure 3, in which the projected one-year lung dose is shown as a function of distance from the release point. For these estimates, considering only the early exposures, lung cancers account for about 85-90% of the predicted fatalities.

Although the emphasis has been on releases from truck mounted spent fuel casks, (based upon analysis and arguments in Sections 6.2 and 6.3) one release magnitude (Case 2) was examined assuming that a rail cask was the source. Although it is not clear that rail traffic would necessarily move through urban centers, this limited analysis is included to provide some comparison with truck mounted cask results. It should be recognized that an attack against a rail cask would probably involve larger quantities of high explosive than an attack against a truck mounted cask. The results are shown in Table 10. Comparison of these results with the earlier estimates for the release from truck mounted casks indicates that the estimates of early fatalities and morbidities do not scale linearly with source strength: again, this is because of the threshold models discussed earlier. The predicted latent cancer fatalities do scale approximately as the total source strength for the same population distribution.

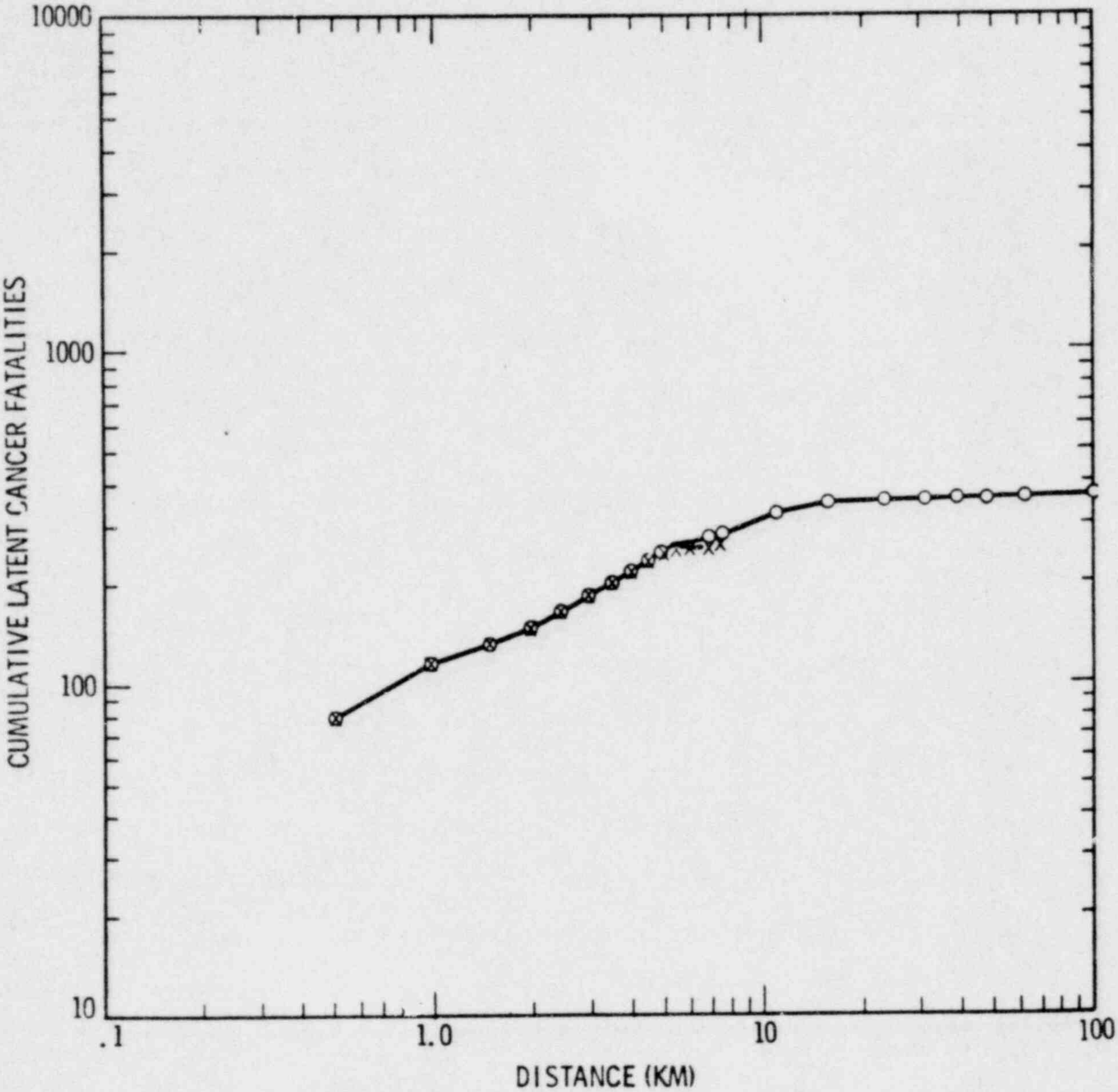

Figure 2. Cumulative Latent Cancer Fatalities as Function of Distance from Release Point (Case 1 Release from Spent Fuel)

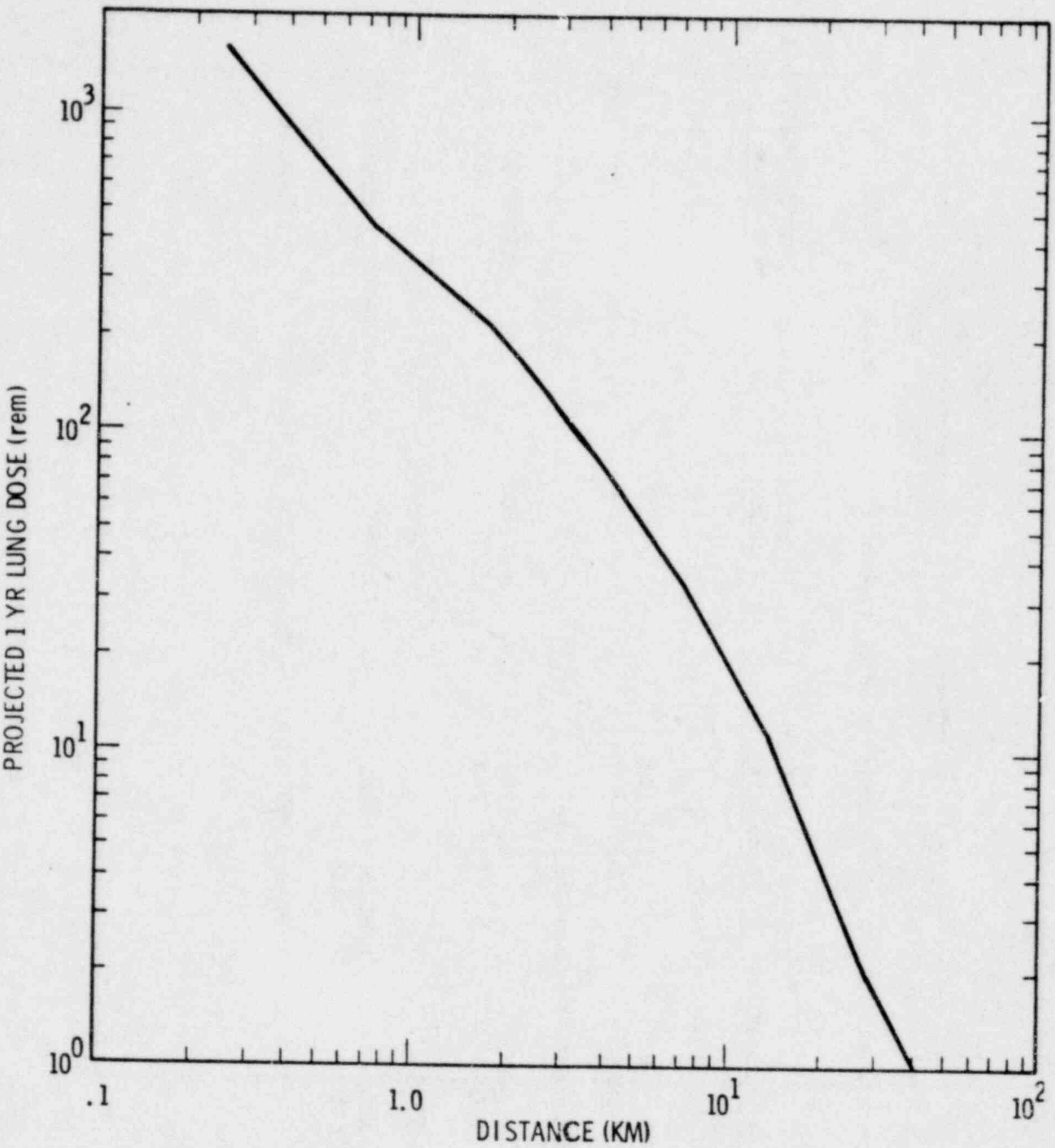

Figure 3. Projected 1-Year Lung Dose as Function of Distance from Release Point (Case 1 Release from Spent Fuel)

TABLE 10

CRAC Consequence Estimates for Release from Railcar Mounted Spent Fuel Cask[1]

Case	Population[2]	Early Fatalities Mean/Peak	Early Morbidities Mean/Peak	Latent Cancer Fatalities Mean/Peak
1. Estimate Without Chronic Pathway				
2	METRAN	130/1200	660/7600	1100/6100
2	METRAN+	130/1200	660/7600	1400/7000
2. Estimate With Chronic Pathway Included				
2	METRAN	130/1200	660/7600	1600/7500
2	METRAN+	130/1200	660/7600	2900/10000

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1 Rail mounted cask contains inventory equivalent to 4.75 MTHM charged to reactor compared to the 1.4 MTHM for truck mounted cask.

2 METRAN is that for the 100 KM square METRAN grid, METRAN+ has population out to 500 miles.

In summary, estimates for latent cancer fatalities made with CRAC agree well with estimates made using METRAN. The analysis indicates that hundreds to thousands of latent fatalities may occur as a result of the largest postulated release in a densely populated area. The analysis also indicates that for such releases, given these population densities, the early fatalities and morbidities occur very close to the release point, and the latent fatalities will be manifest mainly to the population located less than 10-15 km from the release point.

6.4.3 Non-Fissile Isotopes (Large Sources)

As with the spent fuel casks, it was established earlier that any realistic attempt at dispersion can be expected to involve significant quantities of high explosive. The discussion in Section 6.4.2.1 of those consequences directly associated with the employment of high explosives also applies here. Although shipments of non-fissile isotopes can involve large quantities, as much as 10^6 curies, there is usually only a single radionuclide involved, as contrasted to the tens of nuclides involved in a spent fuel shipment.

Both the METRAN and CRAC models were used to estimate the consequences for two levels of respirable release, based upon the summaries in Section 6.3.2.8. The two releases considered were 2% and 0.7% of the total shipment. Based upon the available data,[23] two isotope shipments were examined: 200,000 curies of Co-60 and 15,000 curies of Cs-137 as cesium chloride. The results from METRAN and CRAC are summarized in Table 11. The results from METRAN are for a cell B release averaged over the 3 release times (noon, rush hour and midnight) for a release at midblock. Again, cell B is used because the CRAC estimates assume a release at the grid center and cell B is an adjacent cell.

TABLE 11

METRAN and CRAC Consequence Estimates--
Releases of Non-Fissile Isotopes (Large Sources)

	Early Fatalities[4,5]	Early Morbidities[4]	Latent Cancer Fatalities[4]
A. Cobalt (200,000 Curie Shipment, 2% Respirable Release)			
METRAN[1]	1	50	12
CRAC[2]	0	0	11
CRAC[3]	0	0	17
B. Cobalt (200,000 Curie Shipment, 0.7% Respirable Release)			
METRAN[1]	0.08	16	4
CRAC[2]	0	0	4
CRAC[3]	0	0	6
C. Cesium (15,000 Curie Shipment, 2% Respi.able Release)			
METRAN[1]	0	0.5	0.02
CRAC[2]	0	0	0.1
CRAC[3]	0	0	0.2
D. Cesium (15,000 Curie Shipment, 0.7% Respirable Release)			
METRAN[1]	0	0.04	0.01
CRAC[2]	0	0	.05
CRAC[3]	0	0	.08

1. Average of mid-block release for 3 release times in cell B.
2. Mean from CRAC for grid population only.
3. Mean from CRAC for grid plus population to 500 miles.
4. See Footnote 4, Table 4.
5. See Footnote 5, Table 4.

It may be observed that METRAN consistently predicts early effects while CRAC does not. As discussed earlier, this is not unexpected because of the different techniques by which the two codes handle atmospheric dispersion, cloud depletion, and because of the use of thresholds in METRAN versus dose response curves in CRAC. METRAN has more detail close to the release point and the lower boundary is totally absorbing. Nevertheless, there is essential agreement between the two predictions. In the event of a release from a Cobalt-60 shipment, there could be several early fatalities and tens of early morbidities and latent cancer fatalities. If high explosives are the means of dispersal, then one might expect the immediate effects of the blast to overshadow the radiological effects. Similar results are presented for a release of cesium, albeit the predicted consequences are much smaller than those for the cobalt shipment. Here, especially, it is observed that the effects of using high explosives to initiate the release from a shielded cask can dominate the public consequences of the event.

In summary, the atmospheric dispersal of material from shipments of non-fissile isotopes may lead to tens of early and latent fatalities. The immediate consequences of the use of high explosives in the attack will be comparable.

6.4.4 Less Than Strategic Quantities of SNM

Most shipments in this category involve less than 100 grams of plutonium.[23] Therefore, theft or multiple thefts, followed by dispersal on a city street driven with small amounts of high explosive is postulated. Because it is difficult to get even plutonium dioxide powder airborne in significant quantities, it was assumed for purposes of the consequence estimates that an adversary would not attempt a dispersal with less than 100 grams.

In this analysis, the plutonium mixture employed is characteristic of that from reprocessing of reactor fuel one year after removal from the reactor. The isotopic composition of this plutonium is given in Table 12. Based upon the earlier discussion, 20% of the dispersed material is assumed to be of respirable size. The consequences of an outdoor release were estimated with METRAN and CRAC. The averaged results from the METRAN predictions are presented in Table 13. The METRAN results from a release in cell B are compared with CRAC estimates in Table 14.

TABLE 12
Isotopic Composition of Plutonium Shipment

Isotope	Weight percent/ 1000 gm
Pu-238	1.79
Pu-239	60.65
Pu-240	22.64
Pu-241	10.95
Pu-242	3.63
Am-241	.43
	100.00

*Based upon LWR fuel having 33,000 MWd/MT @ 40 kw/kg burn-up, one year after removal from the reactor.

TABLE 13

Average METRAN Consequence Estimates--
Dispersal of Less than Strategic Quantities of SNM

Cell of Release	Early Fatalities[1]	Early Morbidities[1]	Latent Cancer Fatalities[1]
A. 1000 gm Dispersal			
A	1.1	8.7	110
B	1.6	26	190
C	0.47	13	210
D	1	15	220
B. 100 gm Dispersal			
A	0	1.5	9
B	.0001	2	14
C	0	.31	15
D	.01	1.1	17

1. See Footnote 4, Table 4.

TABLE 14

Comparison of METRAN[1] and CRAC Consequence Estimates -
Dispersal of SNM

	Early Fatalities[3]	Early Morb[illegible]s[3]	Latent Cancer Facilities[3]
A. 1000 gm Dispersed			
METRAN	2	26	190
CRAC[2]	-	-	76/360
B. 100 gm Dispersed			
METRAN	0	2	14
CRAC	-	-	7/32

1. Average values for release in cell B.
2. The second value is the peak value observed in CRAC estimate.
3. See Footnote 4, Table 4

In contrast to the other releases investigated, where early morbidities (especially with METRAN) often equal or exceed the latent cancer fatalities, the latent effects are by far the most dominant from the dispersal of SNM. This is not surprising because the plutonium is an alpha emitter and cancers of the lung (61%) and bone (30%) where the plutonium is deposited, dominate the latent fatalities. This also implies that under the overall assumptions of the study, in the long term, the dispersal of a kilogram of plutonium has the potential to cause significant numbers of fatalities. The METRAN and CRAC estimates again exhibit excellent agreement in the latent predictions. In this instance, the METRAN early estimates are probably more reasonable because this dispersal is essentially a cold cloud as compared to the release from the spent fuel cask.

Neither METRAN nor CRAC were designed to analyze the effects of a release in a confined area, a sports arena, or a stadium. However, in an attempt to explore the effects of such a release, CRAC was exercised for plutonium dispersal with small spatial zones, no heat in the release cloud and a population density that approximates a large outdoor stadium holding 100,000 spectators. These results suggest that tens to hundreds of early fatalities and hundreds to thousands of early morbidities and latent fatalities can be caused. The results also suggest that greater than 90-95% of the effects would be manifest in those exposed at the stadium.

In summary, a public dispersal of approximately 1 kilogram of plutonium would produce a few early fatalities, tens of early morbidities, and a few hundred latent fatalities. A similar release under the conditions of an outdoor sporting event could increase these consequences by an order of magnitude.

6.4.5 Low Level Waste

As indicated earlier because there is so little activity available in low level waste shipments (1000-5000 Ci) it is unlikely that any attempt at dispersal would be made with the intent to create public harm. Nevertheless, because an attack on low level waste could have nuisance value, the effects of a release are considered.

Assuming that 1% of the shipment is released in respirable form, about 50 curies could be released. It is difficult to predict which radionuclides might be included in a specific shipment of such wastes. However, when one considers that the release of 1400 curies of cobalt-60 only leads to tens of casualties and that the release of 105 curies of cesium-137 leads to essentially no casulaties (see Section 6.4.3) in a hyper-urban area, it follows that the dispersal of 50 curies of low level waste is unlikely to result in any illness or fatalities. To support this conclusion, CRAC was exercised for a 50-curie release which contains approximately 30% cesium, 50% ruthenium and 18% strontium. For this situation, CRAC predicts no early effects and less than one latent cancer fatality (i.e., mean and peak values are less than 1).

In summary, a release from low level wastes would pose no significant hazard to the general public.

6.4.6 Consequences of a Release of Radioactive Material--Areas Affected and Economic Impact

In the preceding sections, the METRAN and CRAC models were employed to examine the public health consequences of a deliberate release of radioactive materials from various shipping containers. Another aspect of such releases that must be considered is the extent of the area which may be contaminated by deposition from the passing cloud, and the costs associated with clean-up, including those associated with temporary relocation of the affected population.

At the present time, the METRAN model does not include the capability to follow the cloud precisely, and thereby estimate the actual affected area. However, METRAN results do indicate which cells are affected: that is, those cells within the computational grid in which some concentration of airborne material appears. Figure 4 indicates the cells affected by a specific release from a spent fuel cask in cell B for the three release times considered in the study. The prevailing wind flow is from the south, although the exact direction is a function of time of day and grid locations. Figure 5 is a similar plot for a release in cell C. Estimates for releases in cells A and D exhibit similar behavior. It is possible to extract an estimate of the surface area traversed by the cloud from the CRAC atmospheric dispersal model. Because the area estimate is a mean value from many computations, it is not directionally dependent, that is, it is a mean downwind area. For purposes of comparison, Figure 6 shows the CRAC estimate of cloud coverage superimposed on one of the METRAN calculations.

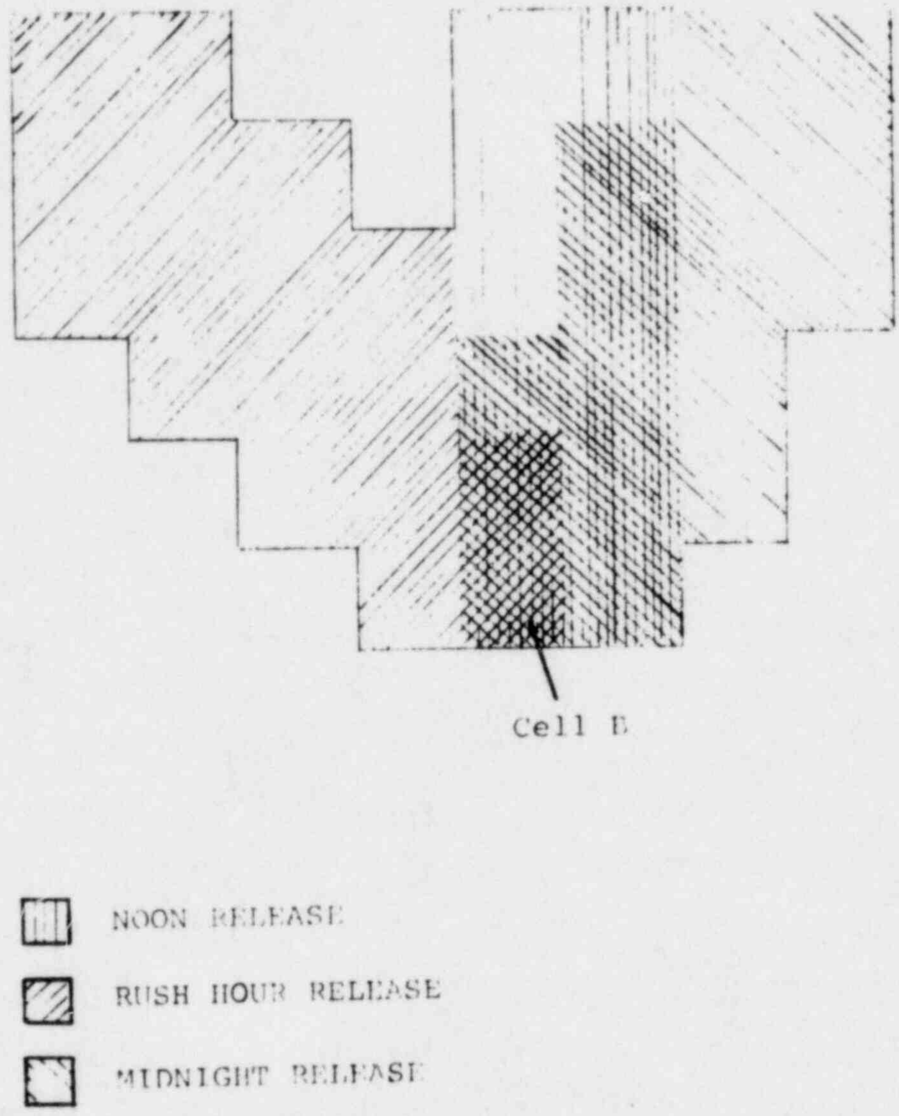

Figure 4. Pattern of Grid Sectors Affected by a Release in Cell B

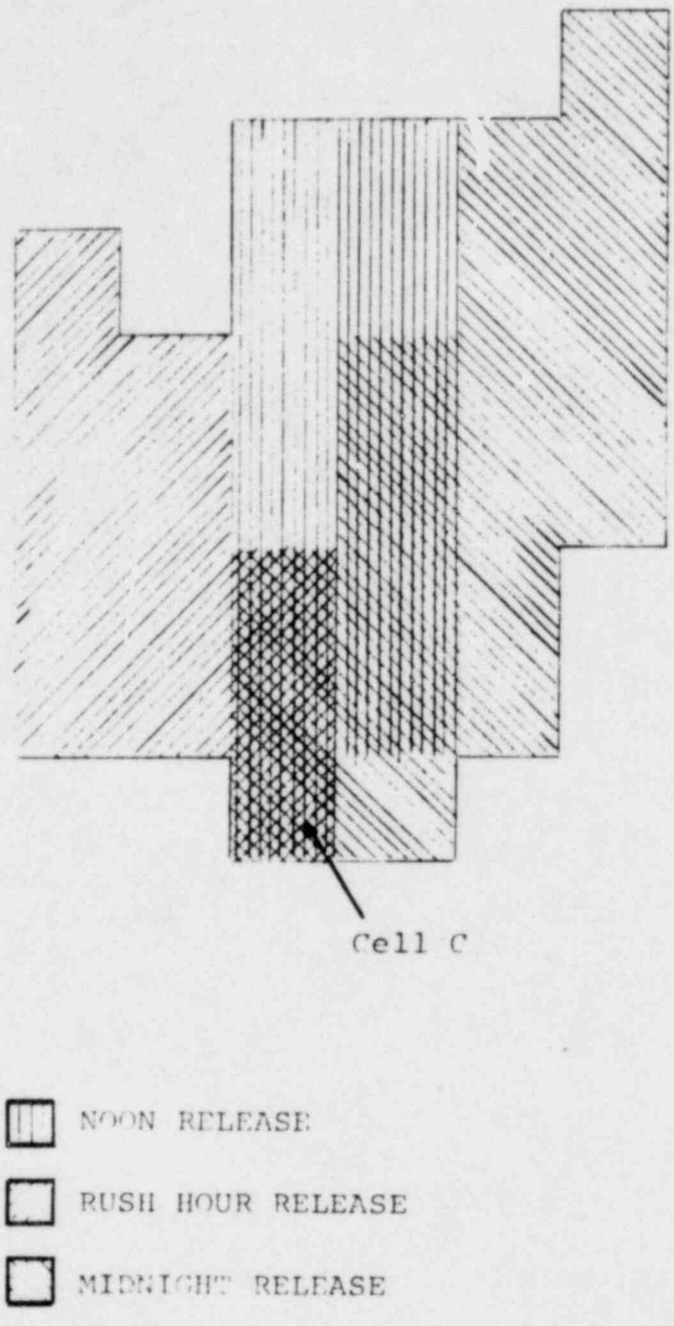

Figure 5. Pattern of Grid Sectors Affected by a Release in Cell C

Figure 6. Mean Area Affected by Release in Cell B (CRAC Estimate) Superimposed on METRAN Cells Affected by Midnight Release in Cell B

This indicates that near the release, the affected area is much smaller than would be predicted by simply counting cells in the METRAN grid in which activity appears. Figure 7 shows the CRAC mean estimate of cloud area out to 100 kilometers from a release.

In order to estimate the costs of clean-up (including temporary relocation) some idea of the potential surface contamination levels is required. For this analysis, it is assumed that those surface areas with more than 0.65 $\mu Ci/m^2$ will require decontamination. This is the clean-up level of the Polomares, Spain nuclear weapons incident,[32] and is also the value that was used in an earlier environmental assessment.[9] For that assessment, data from Operation Roller Coaster[33] were used in conjunction with RADTRAN[34] to estimate the area contaminated to 0.65 $\mu Ci/m^2$ or greater for a given amount of radioactive material released. CRAC was run for several weather sequences and release magnitudes and comparable values were obtained. The relationship between area and release magnitude is shown on Figure 8.

Any attempt at quantifying decontamination costs involves many assumptions. Therefore, of necessity the results here represent only order-of-magnitude accuracy. Any more accurate analysis requires details of land use near the actual point of release (and for larger releases, to considerable distances downwind), the nature of the release (magnitude, radionuclides involved), the weather conditions at release time and for sometime thereafter, etc. Nevertheless, the costs of decontamination may be approximated as proportional to the area contaminated and the population density. The Reactor Safety Study[26] addressed such questions for the case of a reactor accident; similar methodology was used for this study.

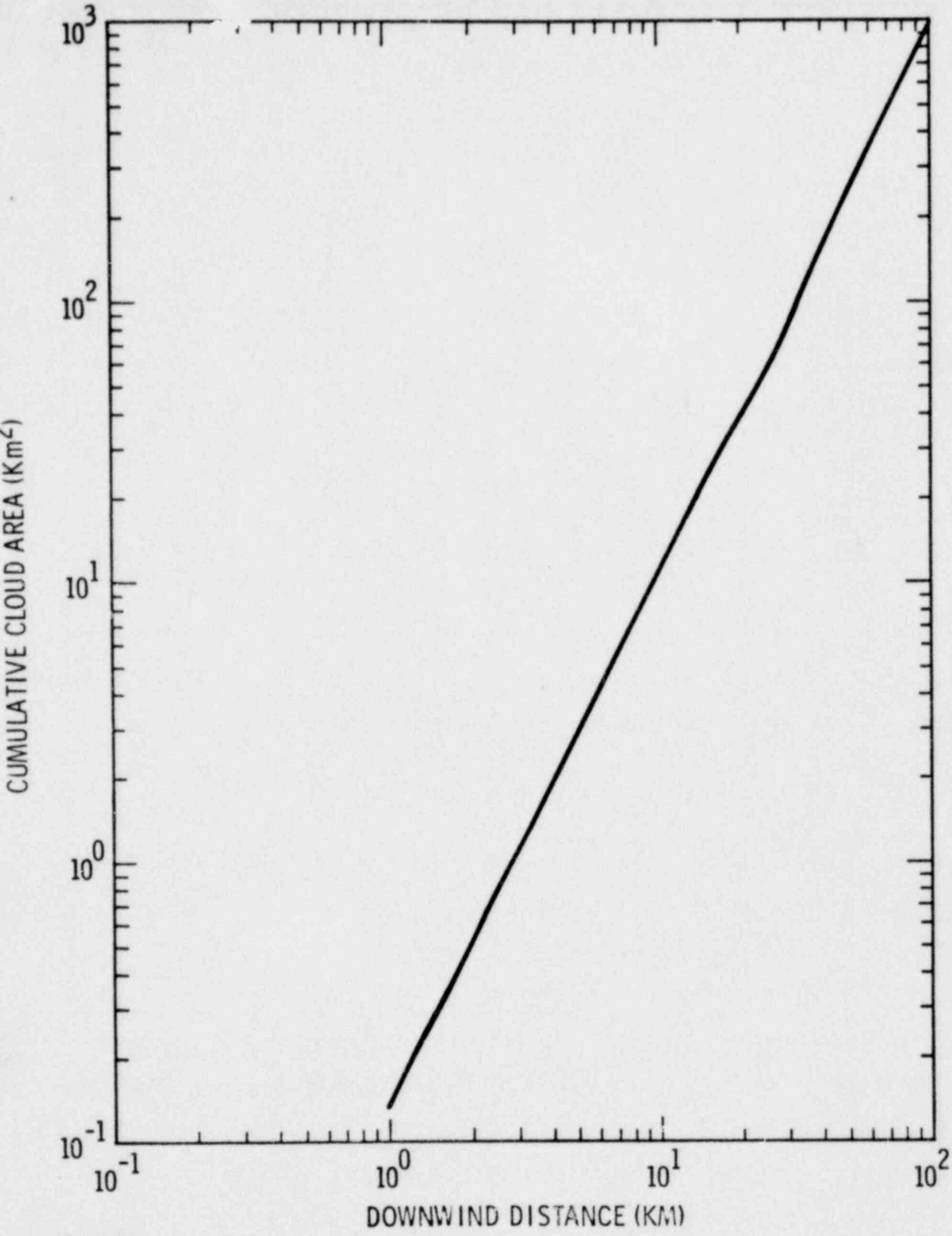

Figure 7. CRAC Estimate of Cumulative Cloud Area as a Function of Downwind Distance from Release Point

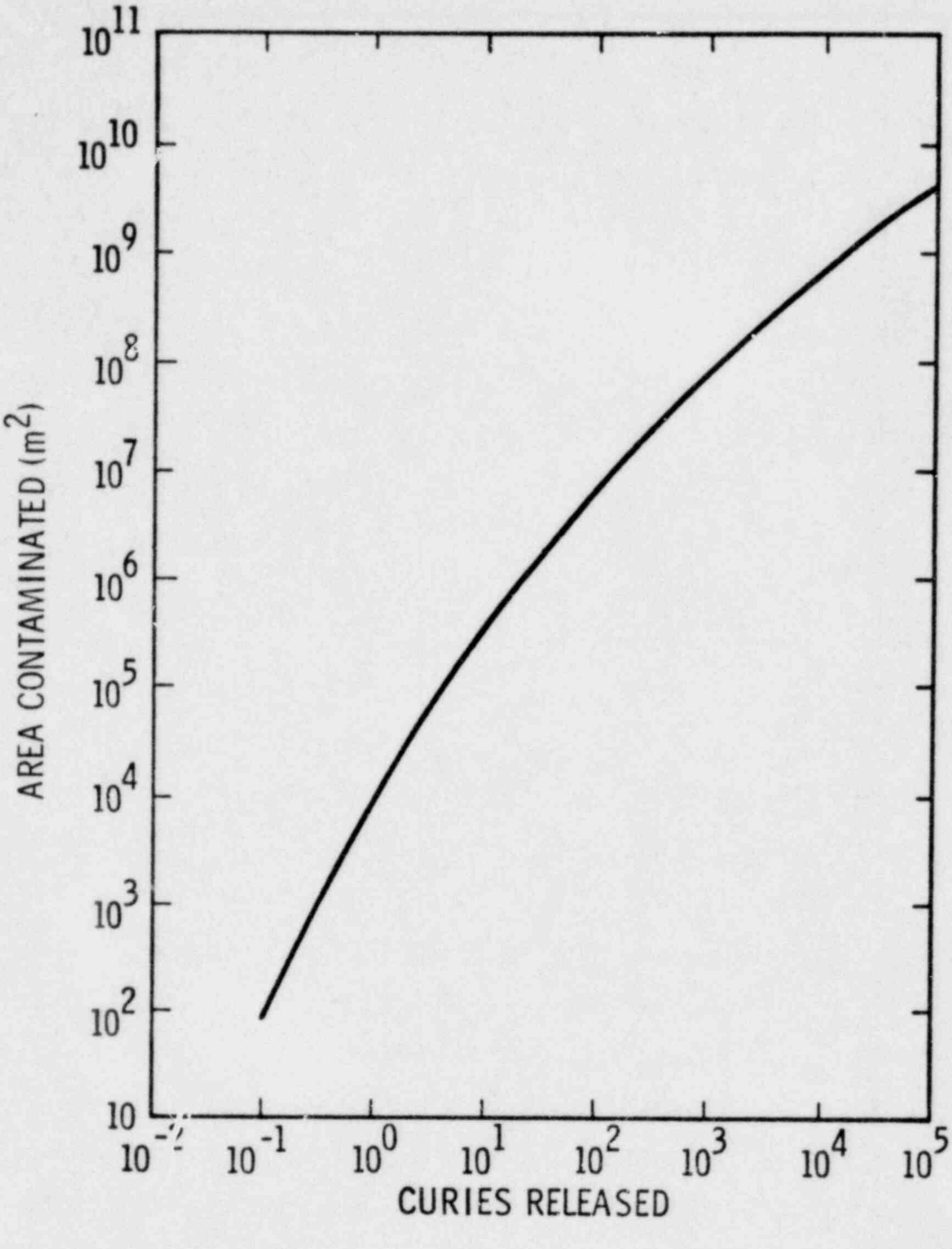

Figure 8. Area Contaminated to a Level of 0.65 $\mu ci/m^2$ as a Function of Total Amount of Curies Released

For the analysis, a population density distribution was established approximating that used for the CRAC health effects estimates. This distribution and associated land use information are shown in Table 15. The results of the analysis of costs associated with the largest release from a spent fuel cask examined (64,000 Ci) are outlined in Table 16. Similar techniques were employed to construct the cost versus release magnitude curve shown as Figure 9. A number of features of this analysis warrant emphasis:

1. This analysis is based upon the release point being within a hyper-urban environment (approximately 39,000 people per square kilometer).
2. This analysis is of necessity only an order-of-magnitude estimate.
3. The analysis does not take into account the repair and clean-up costs that would be associated with the damage resulting from the use of high explosives in the sabotage attack.
4. Although the results imply continually decreasing costs as release magnitude decreases, in all likelihood there will be some minimum cost associated with any public release regardless of size. Likewise, the estimates here imply some "leveling" of costs as release magnitude increases. This has not been adequately verified at this time.
5. The socio-political and economic costs of the loss (however temporary) of the business, finance, and governmental facets of a hyper-urban area have not been estimated or included.
6. Finally, the values here are in 1975 dollars. Projections should take appropriate account of inflation.

TABLE 15

Population Distribution and Land Use Data

A. Population Distribution

Radius from Release (km)	Population Density people/km^2
10	39,000
10-16	16,400
16-48	3,900
48-88	390
88	39

B. Land Use[35]

1. Urban (Pop. Density ~ 3900/km^2)

    20% High Density Residence (6 Story Apts.)

    20% Single Family Residence

    20% Public Land

    20% Industrial and Commercial

    10% Parks

    10% Undeveloped or Vacant

2. Suburban (Pop. Density ~ 390/km^2)

    [illegible].5% Single Family Dwellings

    0.8% Public Areas (Schools, etc.)

    0.4% Commercial and Industrial

    0.3% Parks, Cemeteries, etc.

TABLE 16

Estimated Decontamination/Radiation Cost for a 64,000 Curie Release from Spent Fuel Cask in an Urban Area

		Required DF*	Cost ($)
1)	Decontaminate Apartments	DF ≥ 20 (a)	1.3×10^8
		DF < 20 (b)	$.04 \times 10^8$
2)	Decontaminate Single Family Residences & Farm Homes	DF ≥ 20 (c)	1.1×10^8
		DF < 20 (d,e)	8.2×10^8
3)	Decontaminate Public Land	DF ≥ 20 (f)	1.1×10^8
		DF < 20 (g)	$.1 \times 10^8$
4)	Decontaminate Industrial and Commercial	DF ≥ 20 (h)	2.2×10^8
		DF < 20 (i)	$.1 \times 10^8$
5)	Decontaminate Parks	DF ≥ 20 (j)	$.2 \times 10^8$
		DF < 20 (j)	$.1 \times 10^8$
6)	Decontaminate Vacant Land	DF ≥ 20 (k)	$.01 \times 10^8$
		DF < 20 (k)	$.01 \times 10^8$
7)	Decontaminate Farmland	DF < 20 (l)	$.3 \times 10^8$
8)	Purchase and Dispose of Firage, Crops, etc.	DF < 20 (m)	$.4 \times 10^8$
9)	Temporary Relocation		
	(1,061,100)	DF ≥ 20 (n)	1.4×10^8
	(611,637)	DF < 20 (o)	$.5 \times 10^8$
10)	Income Loss	Individual (p)	2.4×10^8
		Corporate (q)	2.1×10^8
		TOTAL	$\$21.6 \times 10^8$

Notes for Table 16

(a) \$140 per occupant for 6 story apartment buildings (all apartments assumed multi-story).

(b) \$15 per occupant for 6 story apartment building (all apartments assumed multi-story).

(c) Urban and suburban, 5 houses per acre/\$3510 per house (includes street cleanup).

(d) Urban and suburban, 5 houses per acre/\$1095 per house (includes street cleanup).

(e) Rural, \$4915 per building, 2 buildings per 4 person family (home and barn).

(f) \$18,000 per acre.

(g) \$2200 per acre.

(h) \$35,000 per acre.

(i) \$2200 per acre.

(j) \$0.13 per ft^2 to replace lawns/0.61 acres of parks per 100 persons.

(k) \$435 per acre, includes reburral costs.

(l) \$75 per acre (deep plowing).

(m) \$104 per acre (48 state average; if orchards are involved costs would go to \$5000 per acre).

(n) \$13.50 per day per capita; 10 day temporary relocation assumed.

(o) \$13.50 per day per capita; days of temporary location function of radius (3 - 7 days).

(p) \$1100 per capita per quarter quarter $= \frac{\text{avg \# days evac/capita}}{\text{65 working days/quarter}}$

(q) \$940 per capita per quarter.

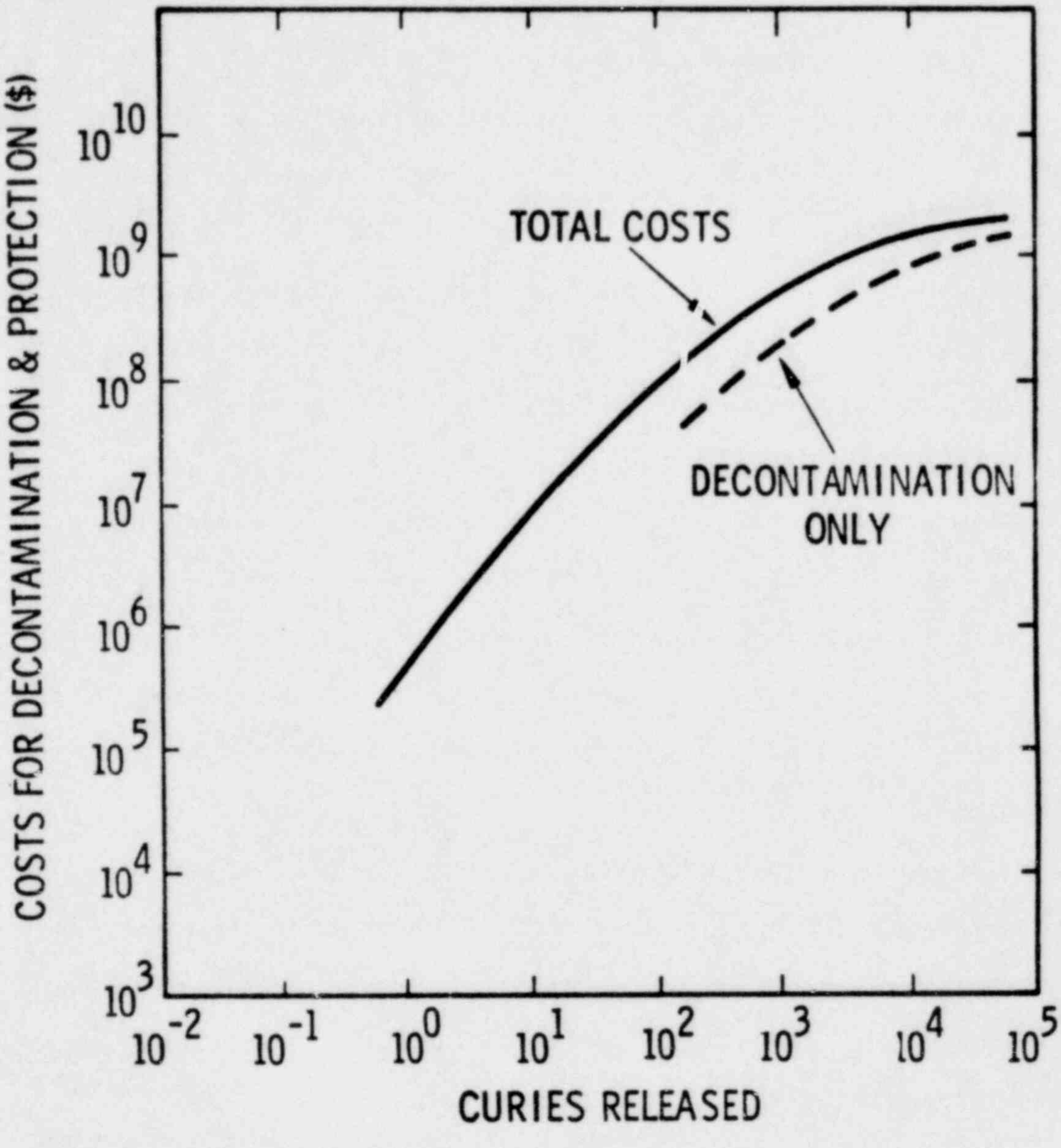

Figure 9. Costs for Decontamination and Public Protection Given a Release in a Hyper-Urban Environment

For comparison purposes, the estimated decontamination costs have been plotted, excluding the costs of temporary relocation and income losses. As modeled, these latter costs are proportional to the postulated length of temporary relocation. Even under the assumption of only a 10-day relocation period, these costs represent 30 to 60 percent of the total. Certainly, some persons would experience much longer periods of relocation, some perhaps even permanently.

Based upon earlier efforts,[9] the area requiring decontamination factors (DF) greater than 20 was considered to be approximately 6% of the total area requiring some decontamination. The analysis is not very sensitive to this assumption. Several estimates were made assuming 20% of the area required DF $\geq$ 20; even so the cost estimate only increased 10-25%.

In summary, the geographical coverage and the economic impact in terms of decontamination costs and income losses have been estimated for a range of deliberate releases within a hyper-urban area. For the largest release examined (64,000 Ci), the impact is spread over numerous political subdivisions, and releases in the range 10^3-10^4 curies are estimated to have costs on the order of 10^9 dollars.

6.4.7 Consequences from Nondispersed Sources

In several of the releases postulated, there may be a substantial amount of material ejected from the shipping container but not aerosolized. That is, it becomes a source of direct radiation, and subsequently a clean-up problem. It was anticipated that this source would not contribute significantly to the public risk. To explore this question, the METRAN code was exercised in the mode used for special form (i.e., nondispersible) material. In this mode, the source is treated as a point source at the middle of an intersection. Therefore, the pedestrian distance of closest approach is the sidewalk. The closest approach for vehicles is the crosswalk, and the vehicles are presumed to be bumper-to-bumper in the lanes in-bound toward the intersection (4 from each direction) while the outbound lanes are empty.

The two shipment types of major concern insofar as direct radiation is concerned are the irradiated (spent) fuel and non-fissile isotope (large sources) shipments because of the strengths involved. In these classes of shipments, release mechanisms were postulated in which substantial amounts of the material are simply ejected from the cask and scattered on the ground. To establish an upper bound, it was assumed that the entire contents were outside the shipping container, which is a conservative assumption in terms of the realistic release mechanisms. The results for such a release during the noon rush hour are shown in Table 17. As one would expect, the latent cancer fatalities as a result of direct radiation are minor compared to the early fatalities and morbidities. Several other points should be noted. First, the early consequences as estimated here are relatively insensitive to the cell of release. This is due to the traffic "packing" assumption described above. As modeled in this noon rush hour, there are about 2 times more fatalities and morbidities among vehicle passengers than pedestrians.

TABLE 17

Consequences of Direct Radiation--15-Minute Exposure

Cell of Release	Early Fatalities[1,2]	Early Morbidities[1]	Latent Cancer Fatalities[1]
a. Spent Fuel (4.8×10^6 Ci)			
A	160	360	1
B	150	340	.5
C	170	380	.3
D	160	360	.8
b. Cobalt-60 (2×10^5 Ci)			
A	43	230	.3
B	42	220	.1
C	45	240	.1
D	43	230	.2
c. Cesium-137 (1.5×10^5 Ci)			
A	0	0	.0006
B	0	0	.003
C	0	0	.002
D	0	0	.005

1. See Footnote 4, Table 4.
2. See Footnote 5, Table 4.

No early consequences are predicted for people in buildings, a fact which is attributable to the assumed distance from the source and the shielding afforded by the building materials. In contrast, the pedestrians and vehicle passengers are given no credit for shielding and the dose to pedestrians includes an albedo term to account for radiation scattering from streets and walls. Third, no early consequences are predicted for the case of a cesium release because of the constraints the model places on distance of closest approach. For comparison purpose, the distances at which dose thresholds for early fatalities and morbidities (assuming 15-minute exposure) are equalled or exceeded are shown in Table 18.

It is clear from the data that direct radiation from the cesium source, even at 15,000 curies, does not pose a major threat to public health and safety. It is also apparent that for those releases involving dispersal and in which there is residual material on the ground, the consequences resulting from inhaled radionuclides far outweigh those from direct radiation. For example, the direct radiation from 1% of the spent fuel inventory ($\sim$ 48,000 curies) may produce tens of morbidities (no fatalities), while the accompanying dispersed material may produce hundreds of morbidities and tens of early fatalities.

Because these estimates were made for an intersection release, some additional hand calculations were run to consider a midblock release. Straightforward examinations of the geometrical relationships between the source and pedestrians, vehicle passengers, and building occupants suggest that a midblock release might increase the early consequences by a factor of 2.

TABLE 18

Dose Threshold--Distance Relationship, 15-Minute Exposure

Dose (rem)	Distance (meters) Pedestrians	Vehicle Passengers
a. Spent Fuel (4.8×10^6 Ci)		
700^1	30	26
400^2	38	33
50^3	88	78
b. Cobalt-60 (2×10^5 Ci)		
700^1	16	13
400^2	20	17
50^3	53	46
c. Cesium-137 (1.5×10^5)		
700^1	2.5	2
400^2	3.2	2.7
50^3	9	8

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1. Above 700 rem $P_f \equiv 1.0$
2. Above 400 rem $P_f \geq 0.4$
3. Above 50 rem $P_m \equiv 1.0$, less than 50 rem $P_m \equiv 0$

One further point must be emphasized. If an attack is sufficiently violent so as to disrupt the shipping container integrity and "spill" the contents, then thousands of pounds of high explosives will have been employed. In light of the possible effects of high explosives discussed earlier (Section 6.4.2.1) it is highly likely that those persons close enough to be affected by direct radiation will have undergone severe physical trauma or died from the explosion, and therefore direct radiation becomes of secondary importance to early consequences.

In summary, although direct radiation could cause hundreds of early fatalities if an entire spent fuel shipment were spilled, for the more realistic modes of potential sabotage, the dispersed material will dominate the public health consequences.

6.4.8 Summary of Consequences

Based upon the release fractions postulated in Section 6.3.2.8 and the public health effects as modeled by the METRAN and CRAC codes, the following radiological consequences have been estimated for the hyper-urban environment.

TABLE 19

Summary of Public Consequences

Source	Early Fatalities	Early Morbidities	Latent Cancer Fatalities
Spent Fuel-Truck	10's	100's - 1000's	100's
Rail	100's	100's - 1000's	1000's
Non-fissile Isotopes (Large Sources)	1's	10's	10's
SNM	1's	10's	100's
Low Level Waste	--	--	1's

*Based upon the largest release fraction postulated for each category.

The economic costs, which are extremely difficult to estimate for the hyper-urban environment, could exceed several billions of dollars.

6.5 Effects of Urban Areas on the Functions of Transportation Safeguards

Unlike the shipments discussed at length above (spent fuel, low enriched fresh fuel and radiography sources, etc.), some shipments of nuclear materials (SNM, such as, plutonium U-233) are currently being safeguarded. Additional safeguard measures have been proposed by the Nuclear Regulatory Commission.[36] In this section, the impacts of the urban environment on the functioning of transportation safeguard systems are considered. Particular attention is paid to the response times, capabilities and tactics of the supporting local law enforcement agencies (LEA), and the effects of increased population and traffic densities in the urban areas as contrasted with suburban and semi-rural areas. There is an active program underway to systematically model transportation safeguard systems including convoy configurations, conflict simulations, law enforcement agency availability, etc.[37,38,39,40] Because this detailed modeling and analysis is still in progress, the observations here are considered to be semi-quantitative to qualitative based upon the available data. The analysis was conducted assuming those systems outlined in the proposed rules to be the first line of response to any threat or attack.

The proposed rule[36] for transportation safeguards incorporates several concepts and features which are summarized here for convenient reference. The proposed rule has three principal objectives:

1. Restrict access and activity in the vicinity of transports.
2. Prevent the unauthorized access into, or removal of strategic special nuclear material from, transports.
3. Provide a response capability (force) to insure that the first two objectives can be accomplished.

For road shipments, whether by special truck or armored cars, there are some additional criteria established. These are:

1. There will be nine armed escorts, drivers may be included, with two in the cargo vehicle.
2. The cargo vehicle will have a bullet-resistant cab and a penetration resistant cargo compartment.
3. There will be at least two escort vehicles which are bullet-resistant.
4. Shipments will use primary highways. (For most urban areas this tacitly implies the interstate highway system or comparable expressways.)
5. There will be continuous radio communication intra-convoy with back-up, and there will be radio contact with a movement control center at least every thirty minutes.
6. There will be communications with local law enforcement agencies (LEA).
7. When stopped (refueling, rest, or emergency only) at least three escorts will have the transport under surveillance with nine available to respond. Two escorts will be sufficiently remote so as to retain contact with local LEA in the event of a single attack.

With these conditions in mind, the effects of the urban environment may be explored. These observations and conclusions on local LEA response and capabilities are based upon a limited analysis of data provided by several thousand local LEA.*

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*The survey was conducted by the International Association of Chiefs of Police for Sandia Laboratories, Department 1710 under Department of Energy programs. The survey responses are being correlated and analyzed and a detailed report will be published. It is emphasized that the observations made here are based upon a limited random sample of the survey responses, and are therefore subject to modification as the full analysis proceeds.

6.5.1 Response Time and Numbers of Local LEA

The limited sample of available data suggests that in very large cities (those with population greater than one million), tens of officers (30-50) can respond to calls for assistance in ten minutes or less. This response usually represents only a small fraction of those on duty, less than 10%. Similar conditions appear to prevail in cities with populations in the one-half to one million category, although the response represents a larger fraction of those on duty, perhaps 25% or so. Even in cities with one hundred thousand to five hundred thousand population, the 10-minute response level is significant, in the range of 10-30. However, in some areas this may be nearly one-half of the total number of officers on duty. In those cities of less than one hundred thousand the response is more like 10 or so, which frequently represents nearly all the officers on duty. In the small cities, less than twenty-five thousand, but greater than ten thousand, the response is typically around 10, but again this represents nearly all those on duty. The actual numbers obviously vary from city to city and shift to shift, the numbers quoted here are "averaged" over three shifts for the cities examined. Nevertheless, the following conclusions may be drawn. In urban areas, the number of defenders (escorts plus local LEA) can be quadrupled in 10 minutes or less, even in smaller cities the number can be doubled. This simple difference in numbers appears to provide the urban LEA and the shipment escorts much more flexibility in responding to an attack than would be the case in small cities or a semirural environment. Also, because the responding force in large cities represents only a small fraction of the officers on duty, the urban LEA should be better able to cope with diversionary or multiple attacks.

If one considers the impact of protracted engagements (1 hour or more) then again the sample suggests that the urban LEA are able to respond with significantly greater numbers, 5 to 7 times the initial response, without necessarily calling upon off-duty personnel or outside assistance. In the smaller cities the total response in one hour may only be two times the initial response and even at that will require personnel other than the duty shift.

6.5.2 Capabilities of Responding LEA, Individuals

It is interesting to note, based upon the sample, that the capabilities of individual officers, in terms of equipment they bring, are not strongly related to the size of city in which they serve. Patrol cars appear to routinely carry shotguns, and in the limited sample examined, about three-quarters indicated that at least some officers would respond with rifles, although the type (automatic or semi-automatic) was not specified. In larger urban areas, cities greater than one-half million, the responding officers would also have gas guns and personal body armor. In the smaller cities, the survey seems to indicate that about one-half the responding officers would be equipped with gas guns and armor. Again, this would certainly appear to provide the urban LEA more flexibility in dealing with a situation.

Individual officer training and experience is less amenable to quantification, but it is likely that the large city forces will have more formal and regular training than those in small cities and towns. It is anticipated that the urban officer is better prepared to handle an armed confrontation than an officer from a semirural area, simply because he meets them more frequently in the course of his normal duties.

6.5.3 Capabilities of Responding LEA, Special Teams

The availability of specially-trained teams to handle unique situations is very much a function of city size. The sample suggests that very large cities most likely have a special weapons team of some type (the so-called SWAT teams), teams of highly-skilled marksmen (snipers) and specially-equipped and trained riot squads. In addition, nearly all the large cities have personnel trained in hostage negotiations and qualified explosive ordnance disposal experts (EOD). All of these special teams have come into existence in large urban areas over the past several decades in response to a variety of socio-political pressures and incidents. In cities of intermediate size (one hundred thousand to one million), the sample indicates that more than half have SWAT, riot control, and explosive ordnance disposal teams. Less than about half of these cities have some sniper team capability, and even fewer have any trained negotiators for hostage situations. In cities smaller than one hundred thousand, less than one-half have any special teams, SWAT, sniper, riot control, or hostage negotiation. Above twenty five thousand, about half will have some EOD capabilities, but such capability is nonexistent in smaller cities.

The obvious conclusion is that the larger the city, the more likely it is to have specially-trained teams. Again, this provides the urban LEA with more flexibility in response to an attack on safeguarded shipments, as well as the ability to bring specially-trained personnel into the action. The only drawback is that the response time of such teams is typically on the order of thirty minutes, so that the escorts and the initially responding LEA would have to hold the situation until the special teams arrived.

6.5.4 Capabilities of Responding LEA, Equipment

As one might reasonably expect, the information in the survey again suggests a strong dependence upon city size. For example, more than one-half of the cities with greater than one million population possess some type of armored vehicle. Cities under one million typically do not, but rely instead on agreements with the National Guard or State Police. Cities larger than five hundred thousand nearly always have equipment vans and special communications vans (obviously correlating with the existence of special teams). Cities under twenty-five thousand seldom have either item, while about half of the cities between these two extremes will have one item or the other. In terms of airborne support, it appears that all of the larger cities have police helicopters and about half also have fixed wing aircraft. In cities of one hundred thousand to one million, better than one-third have helicopters and less than one-third have aircraft. Below one hundred thousand population, city-owned helicopters and aircraft are nearly nonexistent and below twenty-five thousand, they are nonexistent.

As with the special teams, other pressures--some routine, some extraordinary--have caused the urban LEA to be better equipped and prepared to respond to a variety of threats and events. Certainly, the availability of armored vehicles and air surveillance put the urban LEA in a better position to cope with an armored attack than that in which the semi-rural LEA finds itself.

6.5.5 Influence of Higher Traffic Density

There is perhaps a natural tendency to believe that the increased traffic density of the urban area as compared with the rural area will automatically inhibit the response of law enforcement agencies. This tendency is no doubt strengthened by the personal experience of bumper-to-bumper vehicles in rush hour city traffic creeping along at a few miles per hour. However, this situation must be examined from the perspective of the proposed rules.

If these shipments are required to use primary highways, this implies that they will move on the interstate highway system or similar controlled access expressways in most urban areas. It is also presumed, although not specified in the proposed rules, that because an escorted shipment is essentially a convoy operation, routing would be selected, or at least scheduled, to avoid the rush hour congestion in or near major urban areas.* With this consideration, it is then appropriate to compare the urban and rural situations based upon the average traffic densities.

The available data on highway use[41] permit some comparison of urban and rural 4-lane and 6-lane two-way highways. Although 8-lane expressways exist in urban areas, they are seldom found in rural areas. For 4-lane freeways (2 lanes each direction) the average urban traffic flow is about 1.8 times the rural average on a vehicles-per-hour-per-lane basis. For 6-lane freeways, this ratio increases to about 6:5. This suggests that in urban areas it will be more difficult to operate a convoy of 3 vehicles. For example, the traffic density on the urban

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*This presumption is based in part on the requirement in the proposed rule to avoid areas of natural disaster and civil disturbances.

freeways (on the order of 1000 per hour per lane for the larger expressways) will make it difficult for the escorts to insure that they can reach the transport quickly because of the tendency of other drivers to "fill-in" gaps which may exist between vehicles by "lane jumping" in an attempt to move faster than the general traffic flow. This situation is further aggravated by the frequent access points in the urban freeway system, with the attendant constant influx of vehicles from side roads. In some urban areas, freeway exits may be as close together as 1/2-3/4 of a mile, while in other areas there may well be tens of miles between exits. Of course, this high frequency of access also works to assist the safeguards system simply because it provides more routes by which responding LEA can reach the scene, and may permit more forces to respond.

This increased vehicle density in the urban area would also make it easier for vehicles carrying an adversary attack force to approach the transport (say in an adjacent lane) without arousing undue suspicion on the part of the escorts. Furthermore, it has been suggested[42] that "staged" accidents could be employed by an adversary to halt the transport vehicle. Again, such events are less likely to arouse suspicion in the urban area simply because of the fact that traffic-delaying accidents are not uncommon on these freeways. Therefore, the escorts will have to be particularly alert for such events. The urban traffic density can also present the escorts and responding LEA with additional constraints on their response to an adversary. The presence of hundreds of "innocent by-standers" in the passing (or stopped) vehicles could generate considerable reluctance on the part of the escorts to engage in an armed confrontation. In fact, this readily available pool of potential hostages could be employed by an adversary to negate or inhibit escort response.

On the other hand, the very traffic density which inhibits the function of the safeguards team, may also have a strong effect upon an adversary. For example, if the transport is effectively immobilized by the crew, then the adversary is faced with attempting by forceful means to open the transport and remove the contents in full view of hundreds of passing vehicles. In light of the current CB radio usage, it is highly unlikely that such an undertaking would go unreported, even if the transport and escort vehicle radios had been disabled. In this regard, numerous postulated scenarios are set in isolated areas away from cities, apparently because of the presumed desire on the part of the adversary to operate clandestinely if possible.[42]

In summary, the increased traffic density in the urban area will make it more difficult to maintain clear access to the transport, and the presence of other vehicles can inhibit escort responses. On the other hand, the same increased traffic density forces the adversary into the open and increases the likelihood of detection and intervention by LEA.

6.5.6 Influence of Pedestrian Density

Upon cursory examination, it would appear that the pedestrian density associated with the urban area would have a detrimental effect upon safeguards. That is, the presence of many innocent by-standers and potential hostages would seriously inhibit the escort response.

However, when viewed in the light of the proposed rule requiring that routes be restricted to primary highways, while recognizing that in most urban areas such routes--generally freeways--are devoid of pedestrians, the pedestrian population will have essentially no effect upon the functioning of the safeguards system.

6.5.7 Influences of Other Urban Characteristics

Other aspects of the urban environment can influence the functioning of the safeguards system, or at least influence the requirements of the system.

For example, in most cities, especially those areas near primary highways, there are numerous shipping terminals, warehouses, factories, etc., many of which are abandoned or at least unoccupied at any given time. This means that if a safeguarded shipment is attacked with theft as the goal, there are many hiding places readily available if the adversary is successful. Therefore, there is increased need for the safeguards system to prevent access to and removal of material. This means that hardware systems, as well as escorts, can play a significant role in protecting material in transit.

This same condition exists with respect to possible handling and processing of stolen material. In most urban areas, especially semi-industrial areas, frequent movements of materials would hardly be noticed. Groups of individuals going in and out of a warehouse would simply be taken as part of the normal work force. Also, in these areas, the necessary utilities are readily available to operate a clandestine laboratory. Again, this places a premium on maintaining control of the material and preventing an adversary from leaving the scene.

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CHAPTER 7

NONRADIOLOGICAL IMPACTS

7.1 Introduction

Certain nonradiological impacts, such as social impacts, effects of chemical toxicity, and impacts resulting from accidents involving exclusive-use transport vehicles can occur during the transportation of radioactive material in urban areas. Many of these nonradiological impacts can only be assessed in a qualitative or semiquantitative manner owing to their origin in human behavior, or the limited availability of technical information. Nonradiological impacts, however, have the potential for substantial effect on the environment and are therefore considered in some detail in this chapter.

7.2 Social Impacts

Social impacts of transporting radioactive materials in urban areas have been assessed by personnel at the University of Texas School of Public Health and Rice University, under contract to Sandia Laboratories. The report of that work is contained in a separate document.[1] Efforts are underway to obtain peer review of this and other work in the social impacts area. After review and consideration of input from the task group, an assessment of social impacts will be included in the First Draft Assessment.

7.3 Possible Impacts from Chemical Form of Material

The following sections of this chapter assess the environmental impact resulting from the chemical toxicity of the radioactive materials contained in the New York City shipment model (see Appendix A).

It has been judged necessary to reduce the large number of potential chemical forms encountered in the transportation of radioactive material to a manageable size. This is accomplished, as discussed below, by first considering the most common shipment forms for materials transported in the New York City area.[2] The list is further simplified by consideration of inhalation toxicity information on permitted industrial exposure levels, which are used to rate the relative toxicity of the various compounds. Comparison of these maximum-permitted air concentrations with potential air concentrations for transportation release accidents yields a semiquantitative ranking by chemical toxicity hazard of radioactive materials transported in urban areas.

7.3.1 Approach

The results of the radioactive material shipper survey[2] estimate the quantities of particular chemical forms for each isotope shipped. The actual chemical formulae established for each isotope are related to information on shipment size. This allows determination of the maximum quantity of a particular chemical that might be released in an accident. Threshold limit values (TLV)[3] and professional judgment have established a relative chemical toxicity scale for all the compounds considered in the New York City shipments model. The scale developed is:

Class 1 = highly toxic

Class 2 = moderately toxic

Class 3 = slightly toxic

Class 4 = practically non-toxic

The values do not reflect the absolute hazard of a particular compound, but simply compare the relative hazards of the materials.

7.3.2 Findings

Table 1 summarizes information on chemical forms and relative chemical toxicity ratings established for the material shipped through the New York City grid. Compounds placed in Class 4 are considered to have greater radiological than possible chemical hazard, regardless of the quantities shipped, e.g., tritiated water (^3H_2O). Compounds designated by Classes 1-3 require further consideration of the number of grams involved in the shipment.

TABLE 1

Toxicity Ratings for Chemical Forms

Isotope	Chemical Form(s)	Rating
Am-241	Am_2O_3 (Americium Oxide)	2
Au-198	Au (colloidal gold)	4
	$AuCl_3$ (Auric Chloride)	2
C-14	Ethylene trichloride and other organic chlorides	2
	$C_6H_{12}O_6$ (Glucose)	4
Ca-45	$CaCl_2$ (Calcium Chloride)	4
Cf-252	Cf_2O_3 (Californium Oxide)	2

The values in the scale do not reflect the absolute hazard of a particular compound, but simply compare the relative hazards of the materials.

7.3.2 Findings

Table 1 summarizes information on chemical forms and relative chemical toxicity ratings established for the material shipped through the New York City grid. The radiological hazard of Class 4 compounds clearly dominates over any chemial toxicity hazard regardless of the quantities shipped. Compounds designated by Classes 1-3 require further consideration of the number of grams involved in the shipment.

TABLE 1

Toxicity Ratings for Chemical Forms

Isotope	Chemical Form(s)	Rating
Am-241	Am_2O_3 (Americium Oxide)	2
Au-198	Au (colloidal gold)	4
	$AuCl_3$ (Auric Chloride)	2
C-14	Ethylene trichloride and other organic chlorides	2
	$C_6H_{12}O_6$ (Glucose)	4
Ca-45	$CaCl_2$ (Calcium Chloride)	4
Cf-252	Cf_2O_3 (Californium Oxide)	2

TABLE 1 - continued

Co-57	$CoCl_2$ (Cobaltous Chloride)	1
Co-60	Co (Cobalt)	1
	$CoCl_2$ (Cobaltous Chloride)	1
Cr-51	Na_2CrO_4 (Sodium Chromate)	1
	$CrCl_3$ (Chromic Chloride)	1
Cs-137	CsCl (Cesium Chloride)	3
	$CsNO_3$ (Cesium Nitrate)	3
	Cs deposited on Zeolite ion exchange resin	3
Eu-152	$EuCl_2$ (Europium Chloride)	2
Fe-52	Fe $C_6H_5O_7 \cdot 5H_2O$ (Iron [III] Citrate)	2
Fe-55	$FeCl_3$ (Iron [III] Chloride)	2
Fe-59	$FeC_6H_5O_7 \cdot 5H_2O$	2
	(Iron [III] Citrate)	2
	$FeCl_3$ (Iron [III] Chloride)	2
Ga-67	Ga (Gallium)	2
	$GaCl_2$ (Gallium [II] Chloride)	2

TABLE 1 - Continued

Hg-197	$HgCl_2$ (Mercuric Chloride)	1
	$C_5H_{11}N_2O_2Cl$ Hg (Chloromerodrin)	1
Hg-203	$HgCl_2$ (Mercuric Chloride)	1
	$Hg(NO_3)_2$ (Mercuric Nitrate)	1
H-3	Thymidine (Organic Labeled Material)	4
	H_2 (Hydrogen)	4
In-111	$InCl_3$ (Indium [III] Chloride)	2
In-114m	$InCl_3$ (Indium [III] Chloride,	2
Ir-192	Ir (Iridium)	2
I-123	Iodinated Serum Albumin	4
	NaI (Sodium Iodide)	4
I-125	NaI (Sodium Iodide)	4
	ICl (Iodine Monochloride)	4
I-131	NaI (Sodium Iodide)	4
	Iodinated Serum Albumin	4
Kr-85	Kr (Krypton)	4
K-43	KCl (Potassium Chloride)	4

TABLE 1 - Continue

Mg-28	$MgCl_2$ (Magnesium Chloride)	4
Mo-99	K_2MoO_4 (Potassium Molybdate)	3
	MoO_2 (Molybdenum [IV] Oxide)	3
	$MoCl_4$ (Molybdenum [IV] Chloride)	3
Na-22	NaCl (Sodium Chloride)	4
Na-24	NaCl (Sodium Chloride)	4
Po-210	Po (Polonium)	3
P-32	$Na_3PO_4 \cdot 10H_2O$ (Sodium Phosphate)	3
	H_3PO_4 (Orthophosphoric Acid)	2
P-33	$Na_3PO_4 \cdot 10H_2O$ (Sodium Phosphate)	3
Ra-226	RaO (Radium [II] Oxide)	4
Se-75	$Se(MoO_4)_2$ (Selenium [IV] Molybdate)	2
	$SeCl_4$ (Selenium Chloride)	2
Sn-113	$SnCl_2$ (Tin [II] Chloride)	3
Sr-89	$SrCl_2$ (Strontium Chloride)	2
Sr-90	$Sr(NO_3)_2$ (Strontium Nitrate)	2
	SrO (Strontium Oxide)	2

TABLE 1 - Continued

S-35	Na_2SO_4 (Sodium Sulfate)	4
	$C_3H_4N_2S$ (2-amino thiazole assumed as form for organic shipment of S-35)	3
Tc-99m	$TcCl_6$ (Technetium Chloride)	2
Tl-201	TlCl (Thallium Chloride)	2
Xe-127	Xe (Xenon)	4
Xe-133	Xe (Xenon)	4
U-233	UO_2 (Uranium [IV] Oxide)	2
U-235	UF_6 (Uranium [IV] Hexafluoride)	2
	U (Uranium)	2
U-238	UO_2 (Uranium [IV] Oxide)	2
	U (Uranium)	2
	$UO_2(NO_3)_2 \cdot 6H_2O$ (Uranyl Nitrate)	2
	$U(SO_4)_2 \cdot 9H_2O$ (Uranyl sulfate)	2

TLV's, when available, were used to establish the actual mg/m^3 of chemical compound that are allowed in a workroom or industrial environment on a day-by-day basis. Since a release accident may produce a considerably different situation, it was necessary to make further computations to compare these values to those encountered under accident conditions.

The results of this analysis are summarized in Table 2. TLV's for the various chemicals were used to estimate air concentrations of particular compounds. Comparison of these concentrations with the largest quantity shipped, also shown in Table 2, eliminates certain compounds on the basis of their chemical toxicity. If the extrapolated values for air concentrations are greater than the quantity shipped, it seems likely that no direct chemical hazard exists, since the original TLV-TWA (Threshold Limit Value-Time Weighted Average) values were for chronic workroom environments. Materials in toxicity Class 4 are eliminated from further consideration at this point.

TABLE 2

Toxicity Class	Chemical Form	Calculated Concentration* (mg/m^3 air)	TLV-TWA** (mg/m^3)	Largest Quantity Shipped (g)
1	$CoCl_2$	.228	0.1(Co)	$4.26.\times 10^{-3}$
	Co	.1	0.1(Co)	8.85×10^{2}
	Na_2CrO_4	.159	0.05(Cr)	3.46×10^{-5}
	$CrCl_3$	1.55	0.5(Cr)	3.38×10^{-5}
	$HgCl_2$	.069	.05(Hg)	9.76×10^{-5}
	$C_5H_{11}N_2O_2ClHg$	.084	.05(Hg)	6.92×10^{-6}
	$Hg(NO_3)_2$	.084	.05(Hg)	1.23×10^{-4}
2	Am_2O_3	-	Not available	343
	$AuCl_3$	-	Not available	6.28×10^{-4}
	Ethylene trichloride	535	535	19
	Cf_2O_3	-	Not available	2.05×10^{-1}
	$EuCl_2$	-	Not available	7.48×10^{-5}
	$FeC_6H_5O_7\ 5H_2O$	6.44	1(Fe)	9.09×10^{-6}
	$FeCl_3$	2.75	1(Fe)	1.18

*Chemical form listed in Column 2.
**TLV-TWA Values were listed only as mg/m^3 of the elements, etc.

TABLE 2 - Continued

2 (cont)	$GaCl_2$	-	Not available	3.51×10^{-3}
	Ga	-	Not available	1.67×10^{-3}
	$InCl_3$	.199	.1(In)	4.78×10^{-6}
	Ir	-	Not Available	109.00
	H_3PO_4	1	1	1.08×10^{-4}
	$Se(MoO_4)_2$	1.05	.2(Se)	3.63×10^{-4}
	$SeCl_4$	.589	.2(Se)	2.03×10^{-4}
	$SrCl_2$	-	Not available	6.32×10^{-6}
	$Sr(NO_3)_2$	-	Not available	1.67
	SrO	-	Not available	8.16×10^{-1}
	$TcCl_6$	-	Not available	5.96×10^{-3}
	TlCl	.119	.1(Tl)	5.57×10^{-5}
	UO_2	.232	.2(U)	$1.13 \times 10^{+7}$
	UF_6	.296	.2(U)	$1.48 \times 10^{+7}$
	U	-	Not available	10^7
	Uranyl nitrate	.422	.2(U)	2.11×10^7
	Uranyl sulfate	.498	.2(U)	2.49×10^7

TABLE 2 - Continued

3	CsCl	2.19	2(Hydroxide)	1.41×10^{3}
	$CsNO_3$	2.53	2(Hydroxide)	1.64×10^{3}
	Cs on Zeolite Resin	-	Not available	1.15×10^{3} (Ca)
	K_2MoO_4	12.03	5(Mo)	5.1×10^{-3}
	MoO_2	6.58	5(Mo)	2.79×10^{-3}(?)
	$MoCl_4$	12.01	5(Mo)	5.09×10^{-3}
	Po	-	Not available	2.33×10^{-1}
	Na_3Po_4	-	Not available	3.77×10^{-4}
	$SnCl_2$	3.36	2(Sn)	1.66×10^{-4}
	$C_3H_4N_2$	-	Not available	6.95×10^{-5}

In order to put the information in Table 2 in perspective, it is useful to compute an upper bound on the TLV-TWA. If dispersion data from small time-steps* are averaged and used as an upper bound, a maximum concentration of approximately 10^{-4} gm/m^3/gm released is computed. By combining this information with the maximum shipment sizes listed in Table 2, several shipments whose sizes are too small to yield a concentration greater than TLV-TWA can be eliminated. The remaining shipments are listed, by toxicity class, in Table 3.

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*See Appendix F for a discussion of the integration of dispersion factors and time-steps.

TABLE 3

Shipments Remaining After Considering Minimum Possible Dilution

Toxicity Class	Material	Maximum Shipment Size (gm)
1	Co	885
2	Am_2O_3	343
	Cf_2O_3	205
	Ir	109
	$Sr(NO_3)_2$	1.67
	SrO	.816
	UO_2	1.13×10^7
	UF	1.48×10^7
	U	1.0×10^7
	Uranyl nitrate	2.11×10^7
	Uranyl sulfate	2.49×10^7
3	CsCl	1410
	$CsNO_3$	1540
	Cs on Zeolite Resin	
	Po	.233

By examining Table 3, several more materials can be eliminated. First, Co, Ir, Zeolite resin, and U are shipped in metallic, and therefore nondispersible, form. Second, compounds containing dispersible Am, Cf, Sr, Cs, and Po present a radiological hazard which is considerably more significant than any chemical hazard. By eliminating these, a set of materials remains which fulfill the following requirements:

1. Dispersible materials.
2. Shipped in sufficient quantity to potentially exceed TLV-TWA under some conditions.
3. Chemical toxicity is more significant than radiological toxicity.

These materials are listed in Table 4.

TABLE 4*

Significant Chemically-Hazardous Materials

Material	Total Amount Shipped per year (gm)	Maximum Shipment Size (gm)	Maximum**** Amount Aerosolized	Average Shipment Size	Average**** Amount Aerosolized	Threshold** Size for Effect (gm)
UO_2	1.2×10^9	10^7	5×10^5	9.2×10^3	4.6×10^2	2.3×10^3
UF_6	5.3×10^7	10^7	5×10^5	2.3×10^4	1.1×10^3	3.0×10^3
Uranyl nitrate***	5.2×10^5	1.3×10^5	6.5×10^3	6.8×10^3	3.41×10^2	4.2×10^3
Uranyl sulfate	2.8×10^{10}	10^7	5×10^7	2.5×10^5	1.2×10^4	5.0×10^3

*Data extracted from report X1.G of Reference 2.

**Assuming a maximum concentration of 10^{-4} gm/m^3/gm released.

***Includes shipments listed as "salt" in Table X1.G of Reference 2.

****Assuming .05 aerosolized for large shipments. (See Appendix A, Section 9.2.3.)

If it is noted that 5 percent of a large shipment may become aerosolized as discussed in Appendix A, Section 9.2.3, the sole shipment which appears to be a significant chemical hazard (based on average shipment size) is uranyl sulfate. If maximum shipment size is the prime consideration, any one of the materials could prove significant.

Using specific data from Reference 2 for NYC, one finds that 82 percent of the uranium actually shipped through is in dispersible form. The largest of these dispersible shipments is only 15 kilograms (UF_6) and, as a result, would not pose a chemical toxicity hazard.

Other forms of absorption into the human body are not considered in this section since the likelihood of significant quantities of an airborne material being percutaneously absorbed or ingested is less significant than inhalation following an accident.

7.4 Nonradiological Impacts from Transport Exclusive-Use Vehicles

Because radioactive materials are a negligible fraction of the total shipments of all cargo, the only nonradiological impacts which can be attributed to radioactive material shipments are those which result from shipments in exclusive-use vehicles. To consider the nonradiological risks in transportation accidents for exclusive-use vehicles, previously-developed methods[4] are used. Data from Reference 5 provide accident information for fuel cycle shipments. Since only one reactor was involved in material transport through the grid during the 1975 survey period used elsewhere in this study, values of .03 injuries and .003 facilities per year are obtained for exclusive-use shipments of fuel-cycle material.[5]

The other significant use of exclusive-use trucks is in the shipment of Mo-99/Tc-99m generators. Reference 4 assumes that 10 percent of the generators transported are by exclusive-use trucks. For the New York City study area, this would imply an average quantity of 12 TI per shipment, and a total of 2.83×10^3 shipments per year (see Appendix A - Routing Information) carried by exclusive-use vehicles. The maximum distance traveled in the grid by one of these shipments is 12 km (Appendix A - Section 7). As a conservative estimate, the upper bound of the total exclusive-use vehicle travel in the grid would be 3.48×10^4 km/year. Comparing this distance to data in Reference 4 leads to values of .02 injuries and about .001 fatalities per year.

Similarly for cargo airlines, the assumption is made that routine flights are made primarily for Mo-99/Tc-99m generators. For the New York City study area, a total of 1.16×10^4 air freight shipments of Mo-99/Tc-99m are made. Assuming, again, that 10 percent of all air cargo shipments are exclusive-use shipments gives a total of 1.16×10^3 shipments/year by dedicated carrier. The average air freight shipment distance traveled in the study area is 10 km; thus the total distance traveled is 1.16×10^4 km/year. Using the average accident rates[4] of 1.44×10^{-8} accidents/km these flights would be expected to result in about 1.7×10^{-6} accidents/year. Assuming a crew of two, a value of 3.3×10^{-4} fatalities per year would be expected.

Summarizing, nonradiological impacts resulting from exclusive-use transport vehicles for radioactive materials shipments would be approximately .05 injuries and .0043 fatalities per year.

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CHAPTER 8

ALTERNATIVES

8.1 Introduction

This chapter describes alternatives to, or regulatory changes in, the transport of radioactive materials in urban areas. These alternatives include transportation mode shifts, changes in packaging, and the imposition of route or time-of-shipment restrictions on transport. Alternatives are principally assessed in terms of prospective reduction in the radiological impacts described in Chapters 3-5.

In this consideration of alternatives, it is recognized that decreases in radiological impact may result in corresponding increases in certain economic and social impacts. These latter impacts may be significant when considering alternatives to present transport in urban environs. In addition, the reduction in one aspect of risk may produce an increase in the radiological impact for another aspect of urban transport. Therefore, the most significant environmental impacts and the populations at highest risk are given primary attention in the evaluation of possible alternatives. Only feasible alternatives in terms of the present urban environment, the current transportation system, and present regulatory control are discussed in any detail.

8.2 Alternatives to Accident-Free Transport of Radioactive Materials in Urban Areas

Certain alternatives to the nationwide transport of radioactive materials have been previously considered.[1] These aspects, as well as possible urban-specific alternatives are considered in this section with the objective of reducing environmental impacts from accident-free transport. Special routing, requirements on the time of shipment, other operational restrictions, mode shifts, and package changes--TI reduction are investigated as possible alternatives.

The results of Chapter 3 must be seriously considered in any assessment of these alternatives. These results show that type A packages account for nearly 98% of the accident-free radiological impact. More than 87% of this impact derives from packages shipped for medical purposes. Truck and air transport modes are most significant in terms of exposure of population to external penetrating radiation. Handlers, truck crew, people in air terminals, and warehousemen receive 96% of the radiological impact from accident-free transport.

8.2.1 Routing Alternatives

Most destination points for radioactive material shipments are in or near cities. In addition, most truck routes and air terminals are located near urban areas. To reduce environmental impact by changes in routing to avoid cites would precipitate significant economic and social impacts: major hospitals and the majority of people requiring radiopharmaceuticals are situated in densely populated areas. Since people in close proximity to radioactive material packages such as handlers and truck crew receive the largest impact from accident-free transport, rerouting to avoid high populations would not be effective, even from a radiological viewpoint.

8.2.2 Shipment Time Alternatives

The results for accident-free transport presented in Chapter 3 were obtained using a standard shipments model (see Appendix A) involving actual or estimated shipment start times. In order to assess the shipment start time alternative, calculations were performed assuming all shipments to start at the same time for various times of the day. The results are illustrated in Figure 1. The accident-free impact is highest during the afternoon rush hour and smallest at night, with a maximum difference of 435 person-rem per shipment year. The variation with respect to population at risk is shown in Figure 2. Although dose to handlers and to warehousemen remain constant, dose to truck crew and to people in air terminals decrease substantially during the night. This alternative produces a considerable savings in terms of radiological impact.

8.2.3 Other Operational Alternatives

Handlers, warehousemen, truck crew, and people in air terminals comprise the largest dose groups, as shown in Figure 2. Their exposure to penetrating radiation may be reduced through operational alternatives other than time of shipment. Dose to warehousemen and to people in air terminals may be significantly lessened by reducing storage time and cordoning-off storage areas. Dose to crew may be lessened by use of extra shielding between the truck crew and the cargo. Exposure to truck crews is also reduced by all alternatives which shorten the time of shipment. Handlers receive less exposure when fewer handlings are involved. Containerized shipments of radioactive material for common destinations may appreciably reduce the radiological impact from accident-free transport, although some loading and unloading of cargo in urban areas would be unavoidable.

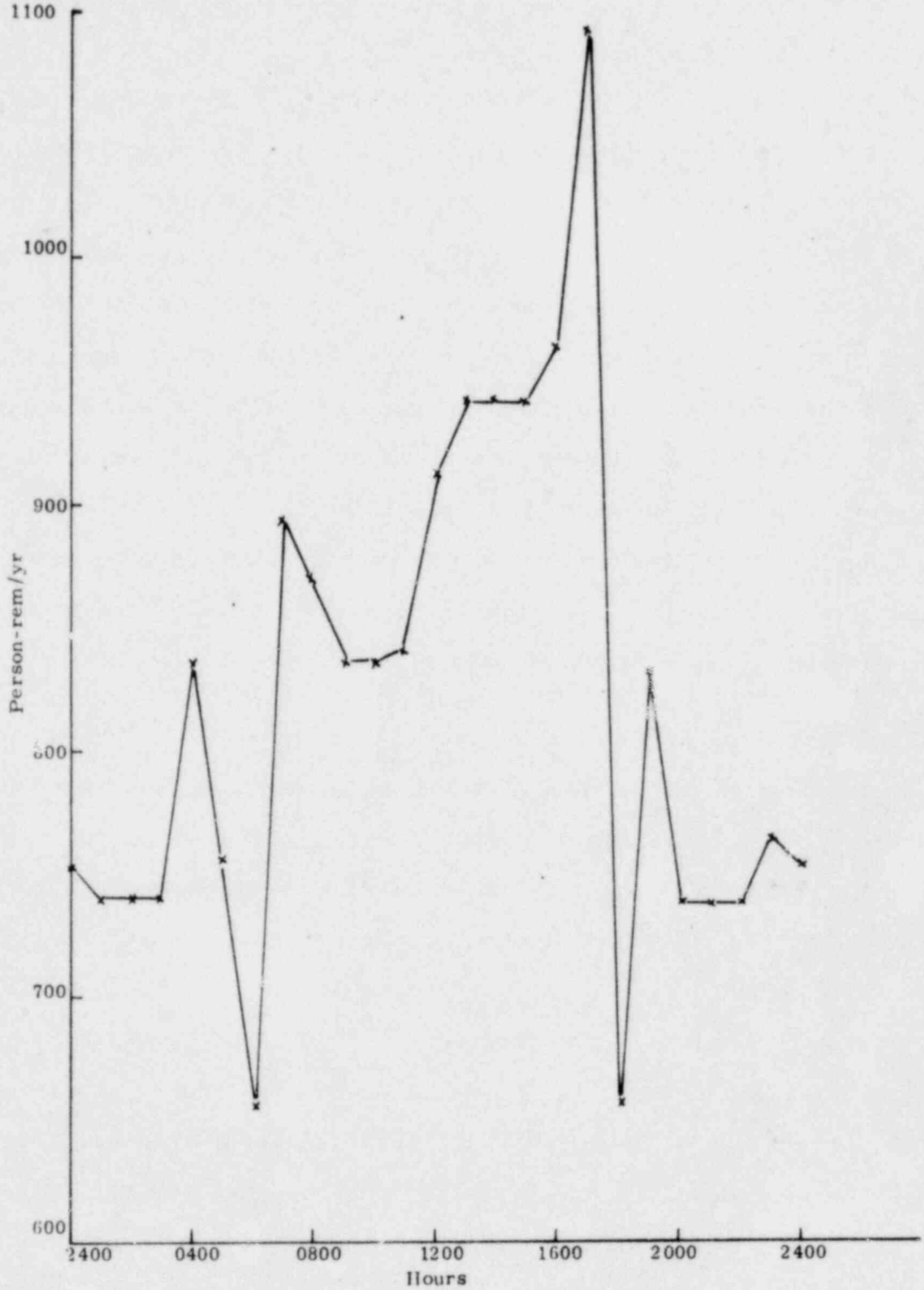

Figure 1. Total Person-Rem/yr. as a Function of Start-Time
(Accident-Free Transport)

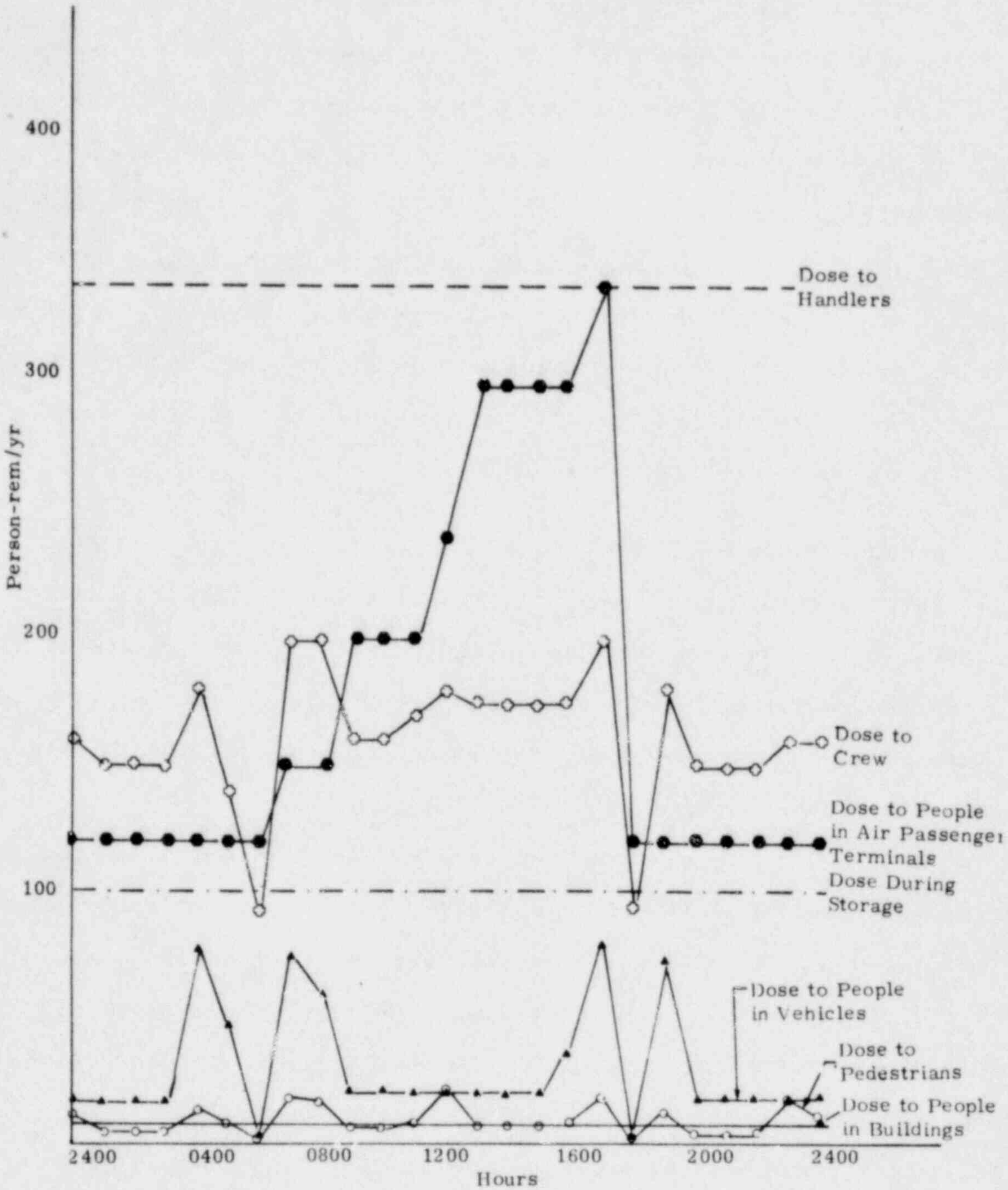

Figure 2. Person-Rem/yr by Dose Group as a Function of Start-Time (Accident-Free Transport)

8.2.4 Transport Mode Alternatives

As discussed in Chapter 3, truck and aircraft/truck mixed modes are the dominant means for transport of radioactive materials in urban areas. Transport mode alternatives of this type were considered in Reference 1. All air transport shifted to truck and all passenger aircraft transport shifted to cargo aircraft increased the impact from accident-free transport of radioactive materials. In view of the present transportation system, which relies heavily on the use of trucks in urban areas, the viable mode alternatives will not be effective in reducing these environmental impacts.

8.2.5 Package Change -- TI Reduction Alternatives

A previous study[1] has shown that lowering the package contents while maintaining the same package shielding will not reduce the impact from accident-free transport unless accompanied by a reduction in TI. More packages would need to be transported and the accident-free impact would actually increase.

A reduction of TI can be accomplished by an increase in shielding: the accident-free radiological impact will decrease in a nearly linear fashion with lower TI* if the average package contents remain constant. A previous study[2] of transport of radioactive material on aircraft showed that the most cost-effective value for TI is 5, but that packages generally average 3 TI--well below the regulatory limit of 10 TI for Yellow III packages.[3] A further regulatory reduction in TI may not be cost effective: most of the packages contributing to accident-free impacts in urban areas are radiopharmaceuticals. Their cost may rise significantly if substantially more shielding is required.

*See Chapter 9.

8.3 Alternatives to Transport of Radioactive Material Affecting Impacts from Vehicular Accidents in Urban Areas

In order to evaluate regulatory alternatives from the perspective of accidents, one must first understand the accident contribution to overall risk. For example, one would not wish to make a regulatory change which might reduce the accident contribution to overall radiological risk but increase the accident-free contribution which is already more significant. Similarly, a regulation which reduced accident risk but increased risks owing to deviations from quality assurance practices would be inappropriate. At the same time, however, the question of reducing maximum consequence accidents must be addressed separately because, even though the contribution of these accidents to the expected value of radiological risk is small, their high political and social visibility makes them items of interest to local authorities, regulatory officials, and the general public.

There are seven basic types of regulatory alternatives which have the potential for affecting the contribution of accidents to both the expected value of radiological risk and the maximum consequence radiological risk. These alternatives are: (1) rerouting, (2) restrictions of the time of day during which shipments are permitted to occur, (3) shipment in sturdier packages, (4) reduction or elimination of shipments, (5) changes in the physical form of the material being shipped, (6) operational constraints on the transporting vehicle or crew, and (7) mode shifts.

8.3.1 Rerouting

Rerouting of shipments within the urban context presents several possibilities. The first, and most extreme, would be total avoidance of urban areas. In reality, this would amount to elimination of shipments whose origins or destinations were within the urban area. It is unlikely that the small reduction in risk would be considered to be of greater benefit than the employment of the numerous medical and industrial radioisotopes used in most urban areas. If through-shipments and transshipments were eliminated, a reduction of perhaps 30% in the expected value of radiological risk from accidents might be obtained in the urban area. However, if it is assumed that these shipments will be made elsewhere, at least part of that 30% will merely be transferred to another locale. If no shipments of extremely hazardous radioactive material have origins or destinations in the urban area (e.g. spent fuel or SNM), this alternative could eliminate the high consequence accidents entirely.

A less restrictive form of this alternative might be to require certain shipments to follow designated "hazardous material shipping routes" which pass through relatively unpopulated areas within the urban center. This alternative, which is already in force in some cities, would reduce early effects from accidents. However, since a cloud of radioactive material would spread across other parts of the city, and the wind direction and speed may vary considerably, the number of long-term health effects such as cancer fatalities and genetic effects would not necessarily be reduced. In fact, they may even increase. Because of the wide use of radioactive materials, it would be extremely difficult to formulate regulations to restrict routing of origin/destination shipments so the overall impact on the expected value of radiological risk f.. these materials would probably not be altered.

A third possibility for rerouting is to require that shipments be made on freeways where possible. To a large degree this is already done because it is economical for the vendor, the user, and the transporter to move the shipment as expeditiously as possible. It would not eliminate the travel in more congested areas because pickups and deliveries would still be required, and the effect of cloud movement away from the area of the accident and over other parts of the city would substantially maintain the expected value of risk. The early effects from maximum consequence accidents would probably be reduced but the long-term effects would probably not change significantly.

The discussion up to this point has applied exclusively to motor vehicle transport. However, three other modes are used: rail, water, and air. In the case of rail and water, rerouting is not feasible since the waterways or railbeds are preexisting. In the case of air transport, noise abatement ordinances generally require that landing patterns for urban airports avoid major population centers where possible. Lower accident rates and fewer urban shipments make the contribution by air transport to expected value of risk negligible. (See Chapter 4, Table 4-5.)

8.3.2 Time-of-Day Restrictions

Travel restriction on radioactive material shipments to nighttime hours would reduce the radiological risk from vehicular accidents, due to the decrease in the population at risk. For example, 90% of the expected value of radiological risk in terms of latent cancer fatalities and 80% of the expected value of radiological risk in terms of genetic effects are attributable to dispersible materials (see Chapter 4, Table 4-7). Of this contribution, about 70% of the latent cancer fatality risk is accrued to people in buildings with most of the remainder to people in vehicles; and about 80% of the genetic effect risk is accumulated by people in vehicles with most of the remainder by people in buildings and pedestrians (see Chapter 4, Table 4-9). The variation of people in buildings and people in vehicles with time of-day for a typical cell is shown in Figure 3. From this figure, it appears that the latent cancer fatality portion of the expected value of radiological risk might be reduced by a factor of ~ 2 if a shipment normally transported during the day were shipped at night. In addition, a factor of ~ 30 reduction in the genetic effect portion might also be obtained by a similar shift. Although this reduction is significant, it should be noted that certain deliveries are currently constrained to daytime. Imposition of such a restriction on transport of radioactive materials may produce certain adverse economic and social impacts.

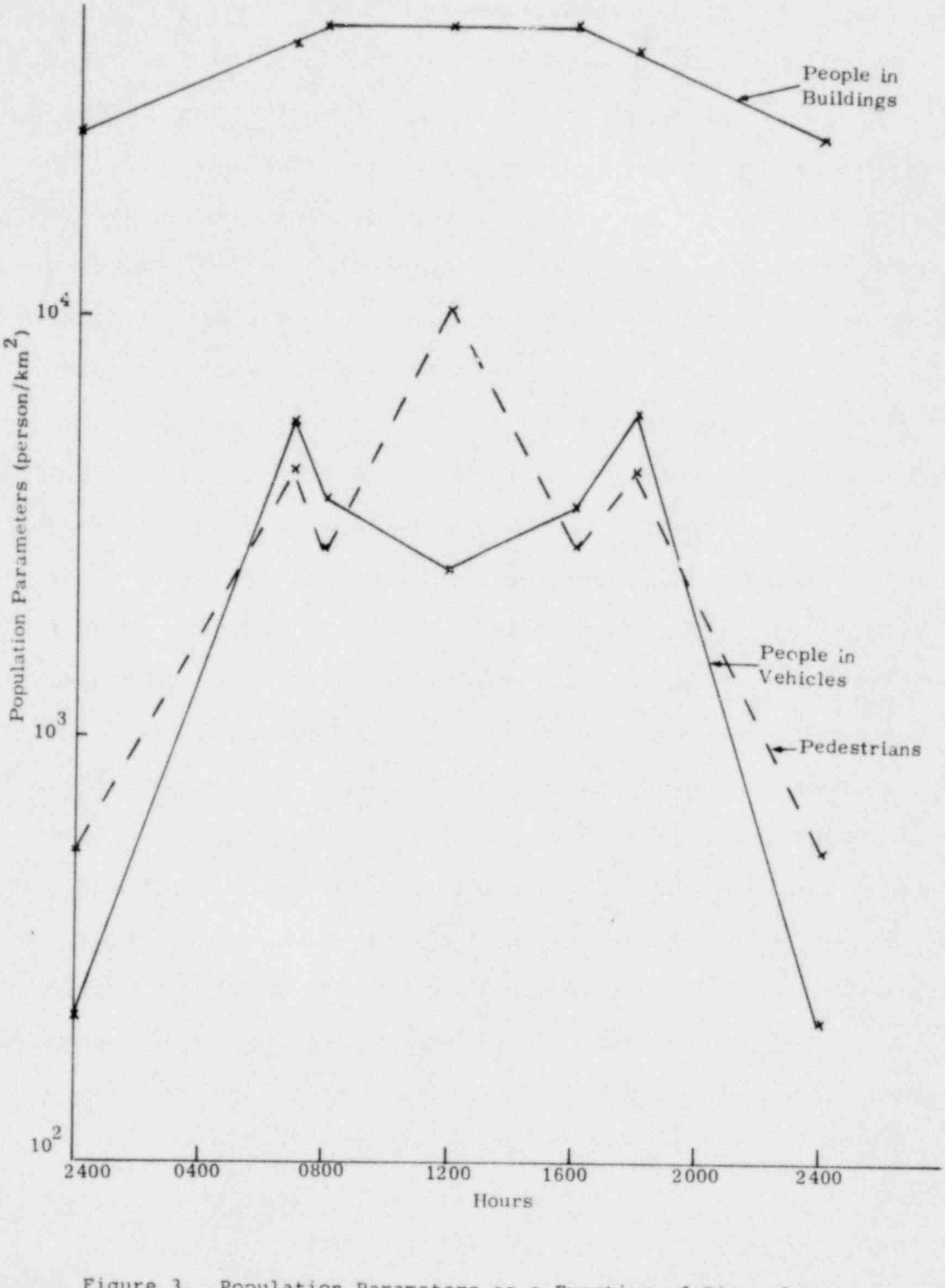

Figure 3. Population Parameters as a Function of Time of Day

8.3.3 Shipment in Sturdier Packagings

If sturdier packaging is required, two main options for compliance are presented to the shipper. He can shift materials currently shipped in type A packages to type B packages or he can obtain sturdier type A packages. In either case, the net result would be to reduce the amount of material which becomes dispersed or unshielded following an accident and to raise the threshold at which accidents begin to affect packages. This clearly would reduce the expected value of radiological risk. This reduction would be significant for latent cancer fatalities since virtually all of the cancer-inducing dose results from loss of package integrity. However, so-called nonrelease accidents cause a significant fraction of genetic effects and this contribution would not be reduced by sturdier packaging (see Chapter 4, Table 4-10).

This alternative could be implemented in a rather straightforward (albeit not inexpensive) fashion for materials shipped in type A packages, since sturdier packages which are licensed are commercially available. In the case of material shipped in type B packages, however, sturdier packagings would probably have to be developed and licensed so the implementation of this alternative for those types of shipments might be less feasible. It should also be noted that in general, packagings are presently more accident-resistant than required by regulatory standards. Therefore, although the standards may be changed, packaging itself might not change at all and still be in compliance with the more restrictive standards. If this were the case, there would be no change in environmental impact.

8.3.4 Reduction or Elimination of Shipments

Reduction of the total number of shipments could be accomplished by bans on use or manufacture within certain geographical areas by rerouting (as discussed above), or by combining shipments to reduce their number. The first of these three options is probably not practical on a widespread basis, although certain endeavors such as nuclear fuel cycle facilities or waste treatment plants might be restricted. In addition, the legal aspects of local or state regulation of nuclear material use/movement are not clear-cut. The second option is discussed in 8.3.1 above. The third option actually increases one aspect of radiological risk because the consequences of a low probability but high consequence accident are increased as a result of the increased amount of material on the shipment vehicle. The expected value of radiological risk remains unchanged because the number of curie-kilometers remains unchanged.

8.3.5 Changes in Physical Form of Material Shipped

A regulation requiring that all materials meet the special-form criteria of 10 CFR 71 and 49 CFR 173 would be extremely costly to implement. Certain materials, notably noble gases and certain isotopes with gaseous daughter products, would be difficult to put in this form. Manufacturing processes and user options might have to be significantly modified. The impact on the radiological risk from accidents would be dramatic (see Chapter 4, Table 4-7). Essentially, the radiological risk could be reduced by an order of magnitude and the impact of low probability/high consequence accident could nearly be eliminated since health and contamination effects would be driven down sharply.

8.3.6 Operational Constraints on Transport Vehicles and Crew

A previous study[1] examined the effect of certain operational constraints, such as reduced speed limits for transport vehicles, and found only a small effect. This type of a restriction would be even less effective in an urban area where speeds are already quite low and highly regulated.

8.3.7 Mode Shifts

The concept of transport mode shift is to require that material be carried on planes instead of trucks, or trains instead of planes. This is feasible when considering the country as a whole but it breaks down when an urban area is considered alone. This is because the urban area tends to be a transportation hub with a large number of origins and destinations. Thus, the urban area is restricted to motor vehicle travel for most materials. In general, mode shifts would be accomplished in connection with rerouting (e.g., spent fuel by barge from Brookhaven National Laboratory to Connecticut instead of by truck through New York City).

8.4 Alternatives Affecting Impacts from Human Error or Deviations from Quality Assurance Practices

This aspect of transport impacts is only tangentially dependent on location in terms of slight changes in radiological consequences. Certain synergistic effects produced independently, but in combination with vehicular accidents, are considered to have extremely low probability. Of the alternatives considered so far, only those involving time of-day, packaging, and operations may significantly affect the environmental impacts resulting from human errors or deviations from quality assurance practices.

8.4.1 Time-of-Day Alternative

Radiological impact as a function of time-of-day is illustrated in Tables 6-8 in Chapter 6. A reduction of 60% in total LCF's is observed when transport of radioactive materials in the urban area occurs at midnight rather than at 4:30 in the afternoon.

8.4.2 Packaging Alternatives

Errors undoubtedly occur at different rates when different packages of radioactive material are handled, labeled, or otherwise employed in the urban transportation cycle. Table 4 of Chapter 5, based on limited data, shows a variation of up to a factor of 3 in human error rates as a function of packaging. Package size or strength certainly affects the incidence or severity of human errors in handling and in other operations, but the precise dependence of the radiological impacts on packaging is the subject of continuing study.

8.4.3 Operations Alternatives

Alternatives in operations such as handling, which minimize human involvement, can lead to reduced environmental impacts. Use of a "two-man rule" or other checks in routine operations, such as labeling, could considerably reduce the effective error rates.

8.5 Summary of Alternatives

Time-of-day restrictions and certain operations alternatives can significantly reduce radiological impacts from accident-free transport of radioactive materials in urban environs. These alternatives can also be effective in lessening the impacts from human errors or deviations from quality assurance practices. Time-of-day restrictions can reduce the impacts from vehicular accidents; rerouting can eliminate low risk, high consequence impacts in urban areas. Sturdier packages may reduce the radiological risk from vehicular accidents.

REFERENCES

1. NUREG-0170

2. Battelle Pacific Northwest Laboratories, Assessment of the Environmental Impact of the FAA Proposed Rulemaking Affecting the Conditins of Transport of Radioactive Material on Aircraft, BNWL-B-421, Richland, WA, September 1975.

3. 49 CFR 173.393 (i).

CHAPTER 9

SENSITIVITY AND ERROR ANALYSIS

9.1 Introduction

This chapter describes the techniques that are used in performing the sensitivity and error analyses of the mathematical models for the environmental assessment of the transportation of radioactive materials through urban areas. Results obtained for the model describing the impacts due to accident-free transport of radioactive material are presented. Analysis of the model used to predict the impact of quality assurance practices and vehicular accidents is ongoing and will be presented in a later report.

The mathematical models described in Appendix D to analyze accident-free transport of radioactive materials in urban areas can be thought of as either a single model with multiple responses, or as consisting of several sub-models. They are treated here as a single model with multiple responses to simplify the description and discussion. These responses are in the form of doses from external penetrating radiation.

The accident-free model is a deterministic simulation model derived from physical principles. It includes all the variables initially considered necessary to characterize the desired responses. Some of these may in fact be found to have no significant effects on the responses.

The input variables relating to characteristics of urban areas used in applying the model are peculiar to New York City. Sensitivity and error analyses are performed on the model to insure that it can be made generic.

9.2 Sensitivity Analyses

The objectives of the sensitivity analyses are to:

1. determine which input variables for the simulation models are important in characterizing the response variables,

2. provide response curves and surfaces which will illustrate how the response variables are affected by changes in the input variables, and

3. provide simplified models on which to perform error analyses.

Formulation of the sensitivity analyses on the simulation models was complicated by the amount of detail specific to the New York City area. For a given route through the 100 cell grid covering a portion of New York City, a number of input variables change with either the time-span, the cell being traversed, or both. These variables, classified by their dependency, for the accident-free model are:

Time-Span Dependent Variables

1. Fraction of intersections at which vehicles stop
2. Freeway traffic count
3. Separation distance between vehicles on freeway
4. Freeway vehicle velocity
5. Persons per vehicle

Cell-Dependent Variables

1. Fraction of grid area occupied by streets
2. Street width
3. Sidewalk width
4. Building wall thickness
5. Building material
6. Number of floors
7. Story height
8. Fraction of grid area occupied by buildings

Time-Span and Cell-Dependent Variables

1. Separation distance between vehicles
2. Vehicle speed
3. Pedestrian density
4. Pedestrian speed
5. Traffic count
6. Population density
7. Shopper population (elsewhere called transient clientele)

The computer code accumulates integrated radiation doses cell-by-cell for the pertinent responses as the shipment traverses the grid on its specified route. To treat the variation in the input variables as they change with time and cell appears counterproductive since the results would be specific to New York City.

Therefore, it was hypothesized that uniform distribution of the total number of persons exposed over the length of the route and time of exposure would be a suitable alternative to accounting for cell-by-cell variations in the input data. For the purposes of the sensitivity analysis, it was decided that the variables would be permitted to vary over their respective ranges, and, for a calculation with a given combination of input variables, that combination would apply for all the cells in the route. This will produce some unrealistic results due to combinations of variables that are inconsistent, e.g., combining highest vehicle velocity with the highest traffic count, but these inconsistencies can be identified and accounted for in the analysis.

The sensitivity analysis consists of fitting the simulation model results with linear models using the methods of statistically designed experiments.[1] Calculations are made with the simulation models for values of the input variables selected according to appropriate experimental designs. The data obtained from these calculations are fitted by linear least-squares models. This method permits the evaluation of effects due to individual input variables as well as those due to their interactions when variables change over their respective ranges. Linearization techniques, by comparison, evaluate the effect of changing one variable at a time with all other variables fixed at nominal values.

The fitting is done using a stepwise regression program.[2] A model is postulated and a set of linear models is obtained by successively examining the contribution of each input variable. The program first admits the input variable in the postulated linear model that explains the most variation in the response variable, and then admits other variables in order of their additional contribution to the overall fit, as measured by their partial correlation with the response variable. As each variable is added, all the variables already admitted are evaluated according to their current contribution, and any time their contribution is not significant at some specified probability level, α_1, the variable contributing least is deleted. The procedure continues until only variables that are not significant at some specified level, α_2, are excluded from the model. From the models thus obtained, the model with the least number of input variables that explain at least some minimum percent of the variation in the response variable is chosen (i.e., has a coefficient of determination, R^2, equal to or greater than some suitable R_o^2).

The linear models to be fitted to the results obtained with the simulation models are of the type:

$$y = \beta_o + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \sum_{j=1}^{k} \beta_{ij} X_i X_j + \epsilon , \tag{1}$$

where

y = the response variable

X_i = the i^{th} input variable

k = the number of input variables

ϵ = the deviation due to lack-of-fit

β_i = the average change in y for a unit change in X_i. (The β_is are estimated from the data.)

9.3 Error Analyses

Once linear models that adequately estimate the outputs of the simulation models are obtained, an error analysis is performed on each of the linear models. The purpose of the error analysis is to estimate the uncertainty in the response variables resulting from errors or perturbations in the input variables.

The error analyses are performed using error propagation formulas derived from Taylor expansions.[3] For example, the relative error in the response variable, y, for a given relative error in one of the input variables, say X_k, can be expressed as

$$\frac{\Delta y}{y} \simeq \left(\frac{X_k}{y}\right)_0 \left(\frac{\delta y}{\delta X_k}\right)_0 \left(\frac{\Delta X_k}{X_k}\right) , \tag{2}$$

where

Δy and ΔX_k are errors or departures from nominal values for y and X_k, respectively,

$\left(\frac{\delta y}{X_k}\right)_0$ is the partial derivative of y with respect to X_k, and the subscript 0 indicates evaluation at nominal value(s).

Equation 2 can be extended to the case of multiple X's, but this is analogous to the worst-case approach to engineering tolerances, and, in practice, results in error estimates that are too large.

9.4 Preliminary Results

The preliminary results consist of linear models considering accident-free transport on four routes (Figures 1-4) for each of the six time spans. The purpose of this analysis is to investigate the effects on the response variables of some of the basic input variables, i.e., time span (TS), photon energy of the emitted radiation (E), and transportation index (TI). The cell- and time-span-dependent variables were permitted to vary as dictated by the times the shipment starts to move in the grid and routes selected.

In addition to the input variables listed in the introduction to this chapter, the following variables need to be specified for each calculation:

<u>Shipment Variables</u>

Photon energy of the emitted radiation, E
Transportation index, TI
Shipments per year
Storage time
Number of handlings
Type of package
Radionuclide

<u>Route Variables</u>

Start time of shipment
Number of cells in route
Cell number
Direction into the cell
Direction out of the cell
Road type
Add time (time outside grid for shipments leaving and re-entering the grid)

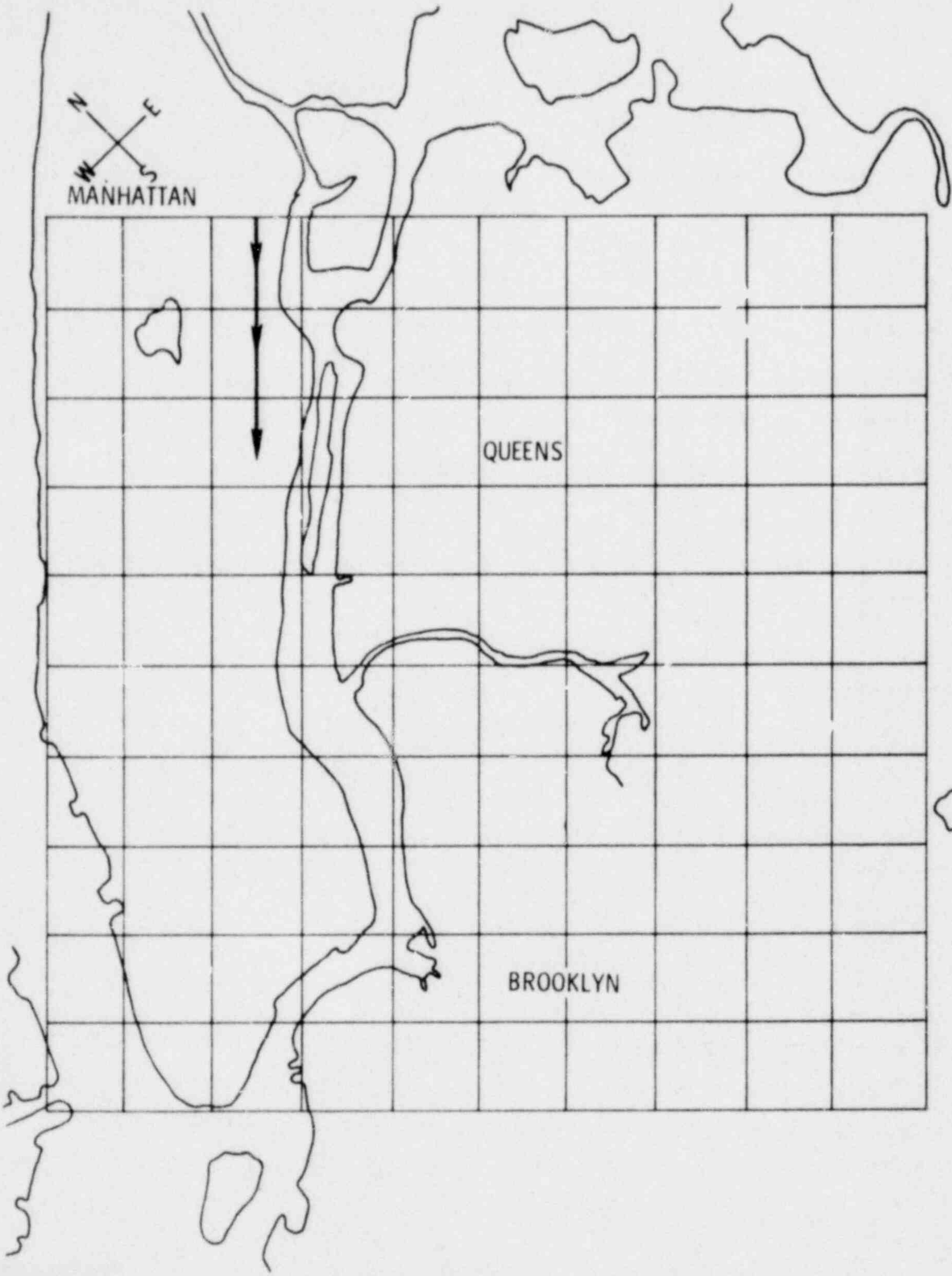

Figure 1. Route 1 - Destination Shipment from Newark, NJ to Sloan Kettering

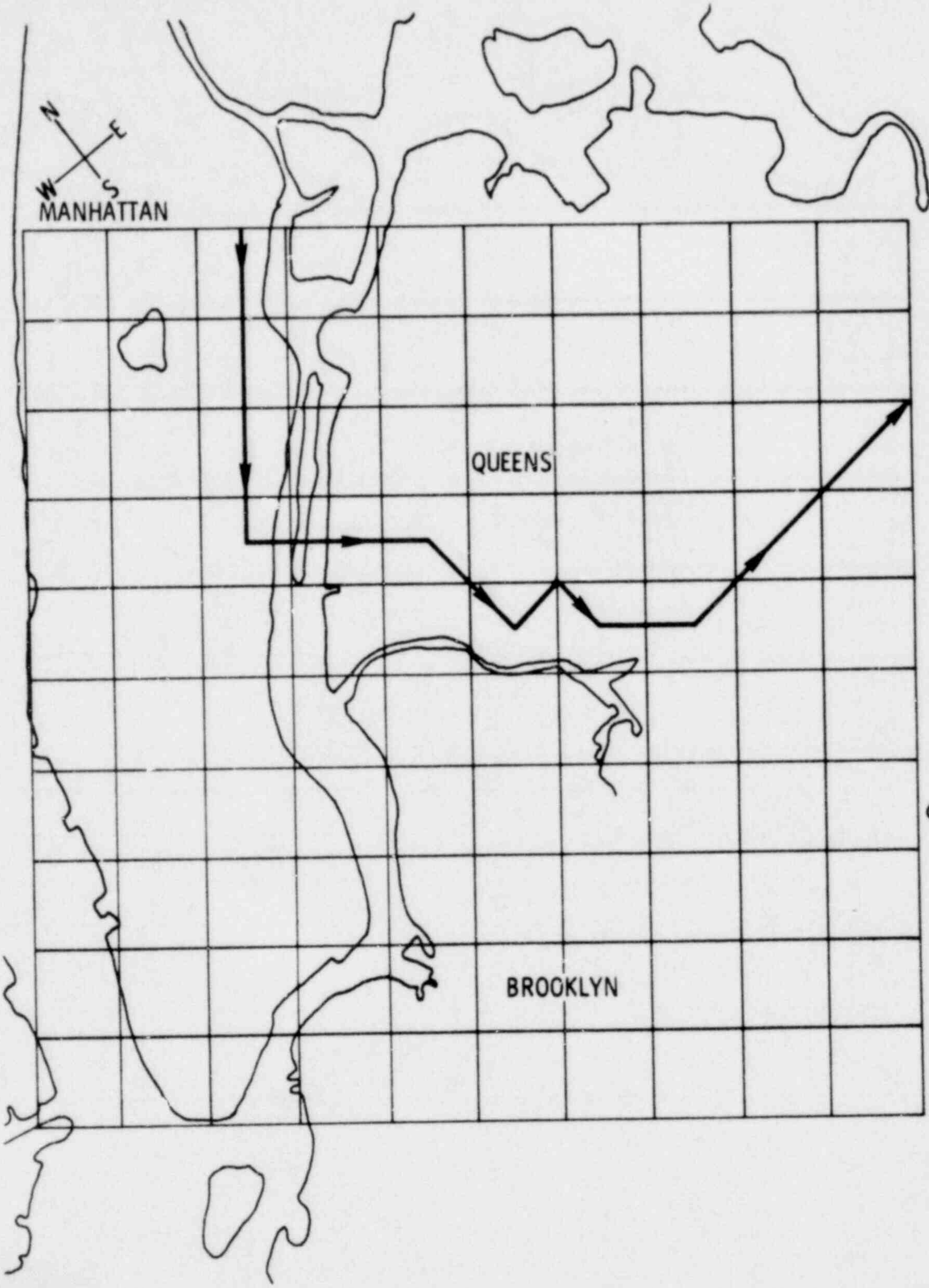

Figure 2. Route 2 - Through-Shipment by Truck from Newark, NJ to Long Island

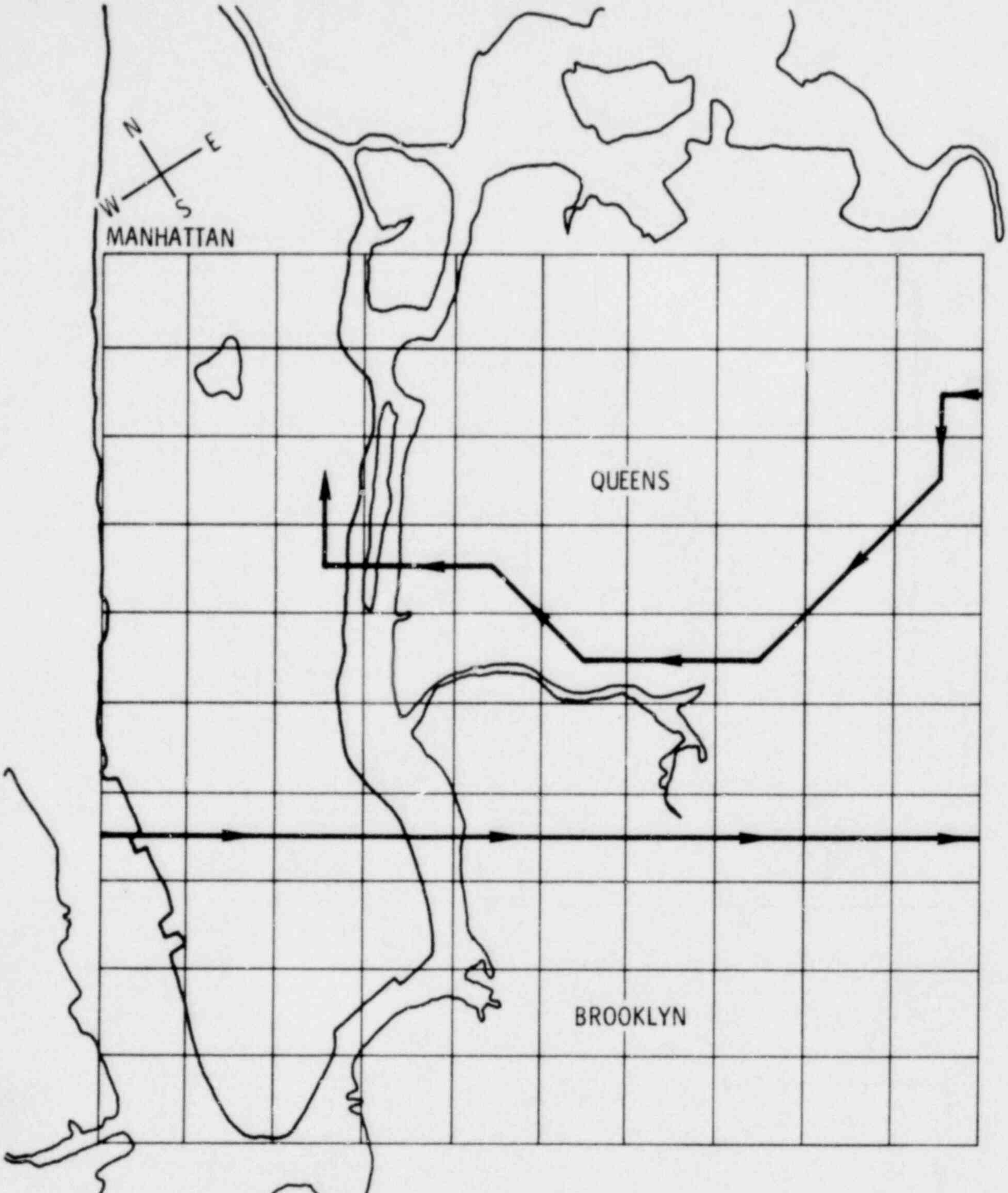

Figure 3. Route 3 - Overflight to J. F. Kennedy and Truck Shipment to Sloan Kettering

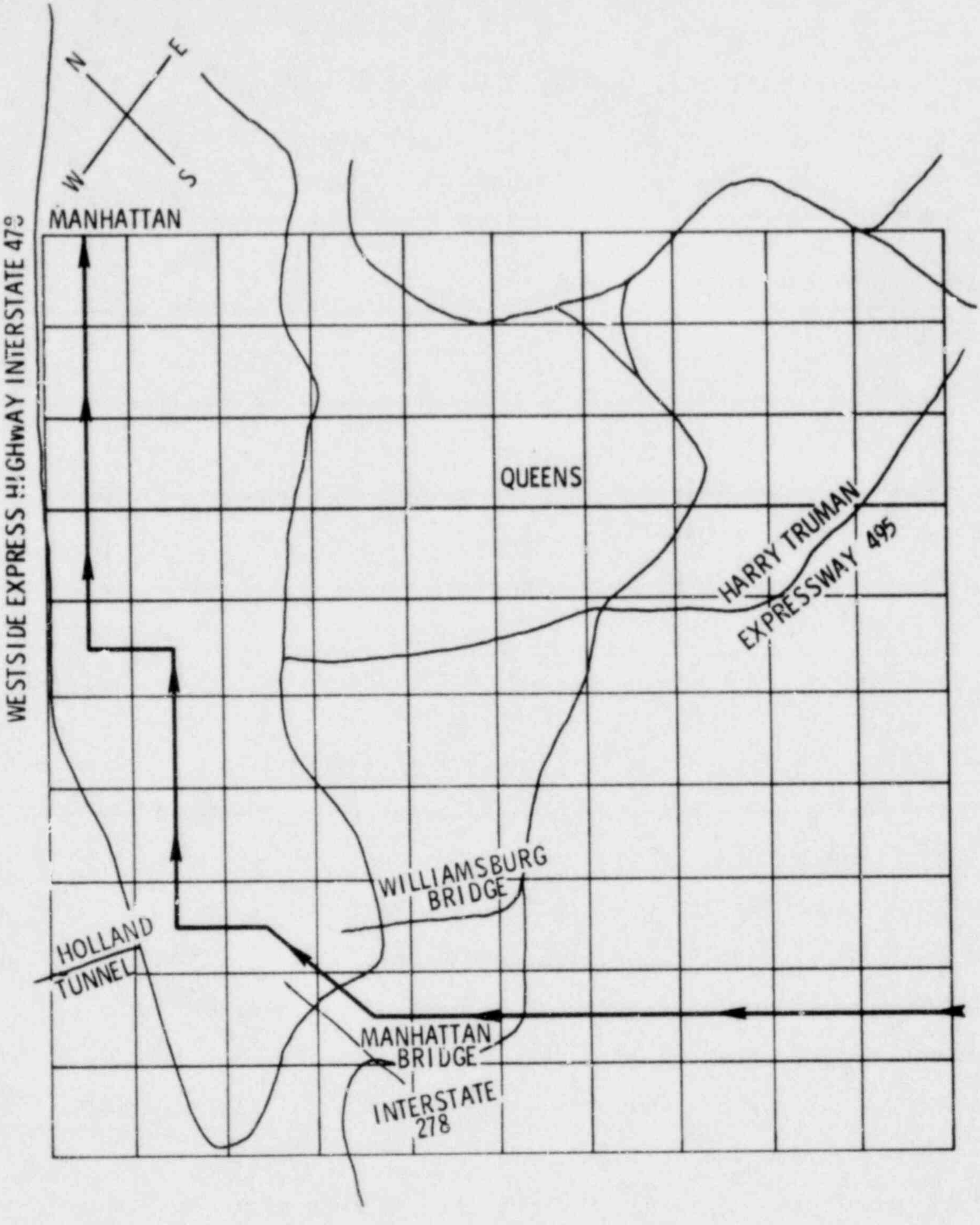

Figure 4. Route 4 - Spent Fuel Cask Through-Shipment

The response variables, appropriate to truck transport, all measured in person-rem, of the simulation model are listed below. Truck was selected as the mode of transport because it is the principal mode used in the area covered by the grid.

Dose to handlers, y_1

Dose to warehousemen, y_2

Dose to crew, y_3

Dose to pedestrians, y_4

Dose to people in vehicles, y_5

Dose to people in buildings, y_6

Total population dose, y_t

The input variables, E, TI, and TS were selected for study because (1) TS affects, among other things, the size and type of population exposed, (2) E and TI characterize the radionuclide being transported and are independent of time-span, cell, and route, and (3) E is implicit in the attenuation coefficient and the build-up factor which appear in all the dose equations except those for handlers. Both the attenuation coefficient and the buildup factor appear in integrals that do not have closed form solutions, and the effect of E is not obvious.

All combinations of two or more input variables, each at two or more levels, is known as a factorial arrangement. The values of E and TI selected for study at each time-span consist of a 3^2 factorial arrangement, i.e., the nine combinations resulting from choosing three equally spaced levels for each variable. These are listed in Table 1.

TABLE 1

Values of Input Variables

Calculation Number	E (MeV)*	TI**
1	.5	0
2	.5	12
3	.5	24
4	.9	0
5	.9	12
6	.9	24
7	1.3	0
8	1.3	12
9	1.3	24

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*The computer code sets values of E that are less than .5 to .5, and values greater than 1.3 to 1.3.

**Values of TI (0,12,24) were used for Routes 1 and 2; the values (0,7,14) were used for Routes 3 and 4. Mo99 has a TI of 24, but the range from 0 to 14 covers the range of TI's for most isotopes in the accident-free model.

The calculations with TI equal to zero were not made on the simulation model. Since TI appears as a product term in all the dose equations, all the doses are zero if TI = 0.

The six time spans are shown in Table 2.

TABLE 2

Time-Spans

No.	Span	Begins	Ends
1	Nighttime	1800	0700
2	Morning rush	0700	0830
3	Morning	0830	1130
4	Noon rush	1130	1300
5	Afternoon	1300	1630
6	Evening rush	1630	1800

The start-times of shipments were chosen at the beginning of a time-span, and all four routes were traversed within the time span in which they started.

The four routes studied (Figures 1-4) are currently used for the transport of radioactive materials in and through New York City. Truck transport was used except for the overflight in Route 3 (Figure 3). The road type was a mixture of two-way streets and freeways as determined by the specific route.

Certain input variables (parameters) are route- and time-span-independent. These were assigned the values shown in Table 3.

TABLE 3

Values of Time-Span- and Route-Independent Variables

Input Variable	Route Number 1	2	3	4
Packages/shipment	1	1	1	1
Shipments/year	1000	1000	1000	1000
Storage time	0	0	12 hrs.	0
Number of handlings/ shipment	1	0	4	1
Type of package	A	A	A	Cask 1

The criteria used in arriving at the linear models are $a_1 = a_2 = .05$, and $R_o^2 = .90$. The equation coefficients, R^2, and the standard errors for the models obtained are shown in Tables 5 through 8. Standard errors are reported as a measure of goodness-of-fit, but since the model is deterministic, they do not have a probabilistic interpretation. Results for dose to handlers, y_1, dose to warehousemen, y_2, and dose to crew, y_3, are not shown in the tables. Dose to handlers, y_1, was not fitted because it can be obtained as a function of TI from Equation 44 in Appendix D without fitting error. Dose to warehousemen, y_2, which was a variable in Route 3 only, is route and time-span-independent and has one form:

$$y_2 = 0.9048\ (TI), \tag{4}$$

with an $R^2 = .9967$, and a standard error of .34 person-rem. Dose to crew, Y_3, was not fitted because, again, it can be obtained directly from Equation 33 in Appendix D. Dose to crew, y_3, is a constant depending principally on the time it takes to traverse a route, and a dose rate of 2 mrem/hr, which is the dose rate limit to the crew for exclusive-use vehicles. The values obtained for dose to crew, y_3, are given in Table 4 below.

TABLE 4

Dose To Crew (person-rem)*

Time Span No.	Route Number 1	2	3	4
1	.345	1.22	.832	2.30
2	1.130	3.84	2.55	7.50
3	.837	2.98	2.05	5.60
4	.990	3.40	2.27	6.60
5	.874	3.08	2.10	5.80
6	1.130	3.80	2.60	7.50

*All results reported are for 1000 shipments/year.

Tables 1 through 4 in the addendum show the linear equations obtained for the four routes. The salient facts obtained from these tables are:

1. All the equations go through the origin, i.e., $\beta_0 = 0$.
2. Excellent fits were obtained for all the equations ($R^2 \geq .90$); in fact most of the equations had values of R^2 greater than 0.99. The smallest values of R^2 were for dose to people in buildings, y_6.
3. With two exceptions, y_4, y_5, and y_t can be expressed as a function of TI alone, and y_6 as a function of the product (E) (TI). The exceptions are for y_t in TS-1 for Routes 2 and 4. For Route 2, y_t is a function of TI and $(TI)^2$, and for Route 4, y_t is a function of (E) (TI).

Response curves and surfaces for y_4, y_5, y_6, and y_t for the linear models are shown in Figures 1 through 36 in the addendum. Although there are many similarities among the plots, all the figures are included for completeness.

The salient facts gleaned from the curves are:

1. The dose levels for type A packaging (Routes 1, 2, and 3) are small compared to those obtained with Cask-1 on a per-shipment basis. See Figures 9 and 36, for example.
2. Time-spans 2, 4, and 6, the three rush hour periods, result in the highest dose levels for all four routes. See Figures 9, 18, 27, and 36, for example.
3. Time-spans 3 and 5, the midmorning and midafternoon periods, give similar results for all response variables, and all four routes. TS-3 doses never differ from TS-5 doses by more than 10 percent for a given response variable and route. See Figures 9, 10, 18 and 19 for example.
4. Dose to pedestrians, y_4, is a small contributor to total dose for time-spans 1, 3, and 5, i.e., it is never more than 10 percent of the total dose.

Neither the equations nor the figures reveals that the estimation error is proportional to the estimated dose, $\hat{y}$. This is not unusual for curves and surfaces that go through the origin, and is an indication that the error may reasonably be expressed as a relative error or as a percent of estimated dose, $\hat{y}$.

Since the time-span- and cell-dependent input variables remain to be investigated, no final conclusions can be drawn at this time about the sensitivity of the accident-free model to all the variables. The following observations summarize the results at present, and will guide the rest of the analysis:

1. Good representations of the accident-free model responses appear feasible
2. E, TI, and TS are important variables, but not for all response variables
3. Simplifications of the models appear possible.

9.5 Sensitivity Analysis for the Time-Span- and Cell-Dependent Variables

9.5.1 Approach

This portion of the sensitivity analysis is performed by permitting the input variables that are time-span- and cell-dependent to change over their respective ranges on a fixed ten-cell route. Instead of permitting a given variable to change from cell to cell as it does in the data base, the variable is held constant in all ten cells of the route.

As a result of the preliminary study of the effects of photon energy, E, transportation index, TI, and time-spans, time-span 2 is combined with time-span 6, and time-span 3 with 5. The four time-spans studied are:

Time-Span 1: Nighttime

Time-Spans 2 & 6: Morning and afternoon rush periods

Time-Spans 3 & 5: Midmorning and midafternoon periods

Time-Span 4: Noontime rush.

The input variables studied, their high and low values, and their mnemonics are shown in Table 5.

The variables held constant are shown in Table 6. They comprise the shipment, route, cell-dependent and time-span-dependent variables. Type A packaging, truck transport, 2-way streets, and masonry buildings are used in this study, because they are the most representative of what is encountered in urban areas.

The eight input variables selected for study are scaled according to a central composite design,[4] which results in each variable taking on five levels: the two extremes, the center, and two intermediate points. In conventional experimentation it is customary to repeat an experiment at the central levels of the input variables in order to estimate experimental error. Since the accident-free model is deterministic, and repeated calculations at the central values produce identical results, only one center point is used.

This central composite design is used because its scaling permits the fitting of second order equations, and because it requires fewer calculations with the model than does a full 3^k factorial arrangement. For example, the central composite design for time-span 1 requires 79 calculations with the model, while 2187 calculations are required for a full factorial.

TABLE 5

Input Variables

Variable	Time Span: 1 Low	1 High	2 & 6 Low	2 & 6 High	3 & 5 Low	3 & 5 High	4 Low	4 High
1. E (MeV)	.5	1.3	.5	1.3	.5	1.3	.5	1.3
2. TI	0	14	0	14	0	14	0	14
3. Distance Separating Vehicles (VSEPDT), meters	88.5	171.1	.6	140.6	.7	143.3	.62	153.1
4. Pedestrian Density (PEDD), persons/km^2	1,275	5,891	10,678	49,322	6,774	31,290	25,200	116,400
5. Traffic Count (TFCNT), vehicles/hr	5	174	.48	1,436	36	1,164	26	778
6. Population Density (PD), persons/km^2	593	63,629	561	104,723	530	15,058	530	15,058
7. Shopper Density (SHOPED), persons/km^2	0	0	16	17,766	16	17,766	16	17,766
8. Number of Floors (NFLR)	1	29	1	29	1	29	1	29

TABLE 6

Variables Held Constant in Study

Shipment Variables	Value
Shipments per year	1,000
Storage Time	12 hrs
Number of Handlings	2
Mode	Truck
Route Variables	
Road Type	2-way
Add Time	0
Cell-Dependent Variables	
Fraction of Cell Area Occupied by Streets	.3
Fraction of Cell Area Occupied by Buildings	.7
Street Width	20 m
Sidewalk Width	3 m
Building Wall Thickness	.38 m
Story Height	3 m
Building Material	Masonry (concrete)
Number of Street Lanes	4
Block Length	200 m

Time-Span-Dependent Variables	TS-1	TS-2 & 6	TS-3 & 5	TS-4
Persons per Vehicle	1.95	2.57	2.48	2.33
Vehicle Velocity, m/s	8.06	3.56	4.08	3.81
Pedestrian Velocity, m/s	2.3	1.79	1.56	1.30

9.5.2 Results of Calculations

The linear equations obtained by fitting the data calculated with the accident-free model are shown in Tables 5 through 10 of the addendum. Coefficients of determination, R^2, larger than .90 are achieved for all response variables except for dose to handlers, y_5, in all time-spans except number one.

In calculating y_5, traffic count (TFCNT), and vehicle separation distance (VSEPDT) are permitted to vary independently; however, the two variables are not independent. The following equations show their relationships:

Time Span	Equation	R^2
TS-1	TFCNT = 590.85 - 3.862 (VSEPDT) 107.9 ≤ VSEPDT ≤ 1.51.7	1.000
TS-2 & 6	TFCNT = 590.73 - 3.861 (VSEPDT) .6 ≤ VSEPDT ≤ 140.6	1.000
TS-3 & 5	TFCNT = 591.34 - 3.844 (VSEPDT) .7 ≤ VSEPDT ≤ 143.3	1.000
TS-4	TFCNT = 586.02 - 3.814 (VSEPDT) .62 ≤ VSEPDT ≤ 1.51.1	.992

These relationships are reflected in the response curves and surfaces, but not in the equations in Table 8 of the addendum.

Figures 37 through 60 in the addendum are response curves and surfaces portraying the effects of the important input variables on the seven response variables. The data analyzed are given in Tables 11 through 14 of the addendum.

For the more complicated responses, the doses to people in vehicles and buildings, only a selection of the possible response surfaces are shown. These are selected to illustrate the effects of the input variables at their intermediate and higher levels. The effects produced at the lower levels of input variables are not shown because of the low levels of the resulting doses.

Table 7 gives the percent contribution of each of the response variables to total dose. Dose to handlers, warehousemen, and crew are the major contributors to accident-free truck transport. Their aggregate average contributions are:

Time-Span	Percent of Total Dose
1	99.6
2 & 6	81.4
3 & 5	90.6
4	86.9

The curves for these response variables, Figures 37, 38, 39, and 60 of the addendum, are simple, straight-line relationships. Figure 40 shows dose to crew, y_3, as a function of transportation index, TI. Linear equations for this variable are not obtained, because the response cannot be fitted adequately with a second order model.

The response curves for dose to people in vehicles, y_5, (Figures 44 - 47 of the addendum) are shown with two scales for the independent variables to show the dependence between traffic count, TFCNT, and vehicle separation distance, VSEPDT. The dose to people in vehicles decreases as a function of vehicle separation distance.

TABLE 7

Percent of Total Dose*

Response Variable	Time-Span TS-1 Mean (min/max)	TS-2 & 6 Mean (min/max)	TS-3 & 5 Mean (min/max)	TS-4 Mean (min/max)
Dose to handlers, y_1	31.1 (29.0/33.3)	19.8 (13.3/23.1)	23.8 (16.0/27.1)	22.0 (14.9/25.7)
Dose to warehousemen, y_2	56.0 (52.5/60.1)	35.6 (24.1/41.8)	42.9 (28.9/48.9)	39.5 (26.8/46.2)
Dose to crew, y_3	12.6 (6.6/17.2)	26.1 (14.9/35.0)	23.9 (13.2/31.9)	25.4 (13.9/34.5)
Dose to pedestrians, y_4	0.11 (.04/.19)	3.7 (1.4/6.1	1.3 (.5/2.2)	5.2 (1.9/8.2)
Dose to people in vehicles, y_5	.08 (.04/.14	13.9 (1.7/42.2)	7.8 (1.0/38.3)	7.6 (1.2/37.6)
Dose to people in buildings, y_6 (person-rem)	.23 (.04/.89	.94 (.12/3.50)	.23 (.05/.88	.25 (.05/.92)
Maximum Total Dose	21.04	30.24	25.84	28.14

*The means for a time-span do not sum to 100% due to rounding.

9.5.3 Conclusions Obtained from Accident-Free Sensitivity Analysis

The major conclusions reached from the accident-free model are:

1. Transportation index, TI, is the most important input variable. It appears in the linear equations for all the response variables.
2. The number of time-spans can be reduced from 6 to 4 by combining morning and afternoon rush periods, and midmorning with midafternoon rush periods.
3. The most important response variables are doses to handlers, warehousemen, crew, and total dose. All of these are simple functions of TI, and are independent of urban area variables. The six response variables ranked according to their contribution to total dose are:

Rank	Variable
1 (largest)	Dose to warheousemen
2	Dose to crew
3	Dose to handlers
4	Dose to people in vehicles
5	Dose to pedestrians
6	Dose to people in buildings.

4. Doses to pedestrians, people in vehicles, and people in buildings have linear equations with imput variables characteristic of urban areas, e.g., PD, PEDD, and SHOPED. The ranges of these variables are likely to encompass the values they might take for urban areas other than New York City. Thus, the conclusions reached should be applicable to urban areas in general.

9.6 Error Analysis

The error analysis for the linear models treats total dose and its three largest components, i.e., doses to handlers, warehousemen, and crew. The other response variables, i.e., doses to pedestrians, people in vehicles, and people in buildings, taken together make up a maximum of 18.6% of total dose. This contribution occurred in the combined time-spans 2 and 6, and the maximum dose in time-spans 2 and 6 is 11.07 person-rem to people in vehicles. The traffic count associated with this dose is 742 vehicles per hour. Hypothesizing that the same pesons are exposed for the 10 km route for the entire year (1000 shipments), the average dose per person is:

$$\text{Average dose} = \frac{11.07 \text{ person-rem}}{\left(742 \ \frac{\text{vehicles}}{\text{hr}}\right)\left(\frac{10 \text{ km}}{12.82 \text{ km/hr}}\right)\left(2.57 \ \frac{\text{persons}}{\text{vehicle}}\right)} = .7 \text{ mrem.}$$

In addition, hypothesizing that a vehicle containing one person is at the minimum separation distance of .62 m from the transport vehicle for the entire year (1000 shipments), the maximum possible dose is calculated as follows:

$$\text{Maximum Dose} = \frac{K_o (TI) e^{-\mu r} B(r)}{r^2} \ \frac{L}{\bar{v}} \ (PPS) \left(\frac{\text{Shipments}}{\text{year}}\right),$$

where K_o = 4.11 for type A packaging

TI = 14

L = 10 km

PPS = 1

Shipments/year = 1000

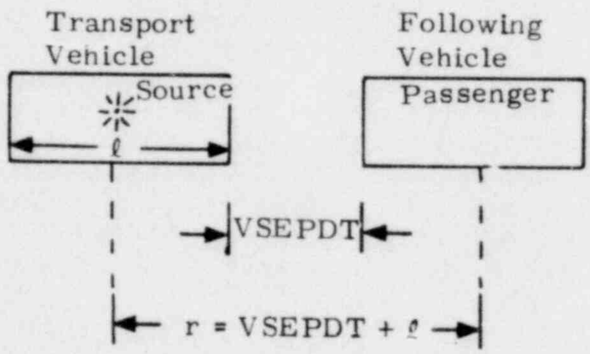
$\bar{v}$ = 12.82 km/hr

μ(air) = .64 x 10^{-2} for E = 1.3,

B(r) = 1 + .00197 x r for E = 1.3,

and r = VSEPDT + ℓ

as shown in the following sketch



For this clearly unrealistic case, the maximum individual dose is 883 mrem/yr.

From these two extreme cases, it is seen that error analyses of the linear equations for doses to pedestrians, people in vehicles, and people in buildings would not add significantly to what has been learned about the normal model.

The linear equations for the important response variables are straight line functions of TI. However, reliable data on the errors expected in TI or its distribution are not available. Consequently, the errors in the responses are evaluated by postulating relative errors in TI.

Using Equation 2, the relative errors in the y's are simply

$$\frac{\Delta Y}{\hat{y}} = \frac{\Delta TI}{TI} ,$$

that is, the relative error in TI propagates directly in the response variable.

9.7 Summary

The total radiological impact from accident-free transport is most sensitive to the doses received by warehousemen, crew, and handlers, which are independent of the details of the urban environment. These doses are simple, linear functions of TI. The dose apportioned to people in vehicles, pedestrians, and people in buildings, obtained for ranges of input parameters which are likely to encompass any U.S. urban area, represent a much smaller percent of the total radiological impact of transportation of radioactive materials in urban areas. Probable errors in these smaller contributors are judge not to strongly modify the total impact.

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3. Tukey, J.W., The Propagation of Errors, Fluctuations and Tolerances, Basic Generalized Formulas, Technical Report No. 10, Statistical Research Group, Princeton University, 1958.

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ADDENDUM

TABLE 1

Equation Coefficients

Route 1

Dose to Pedestrians (Y_4)

Time Span	TI	$(TI)^2$	(E)(TI)	R^2	Std. Error ($X10^3$)
1	.0004	--	--	.9975	.23
2	.0217	--	--	.9975	12.08
3	.0062	--	--	.9973	3.57
4	.0270	--	--	.9976	14.82
5	.0066	--	--	.9976	3.62
6	.0217	--	--	.9975	12.07

Dose to People in Vehicles (Y_5)

Time Span	TI	$(TI)^2$	(E)(TI)	R^2	Std. Error ($X10^3$)
1	.0001	--	--	.9970	.07
2	.0622	--	--	1.0000	3.50
3	.0188	--	--	.9999	2.05
4	.0216	--	--	1.0000	1.45
5	.0170	--	--	.9999	2.16
6	.0661	--	--	1.0000	3.53

TABLE 1 - Continued

Dose to People in Buildings (y_6)

Time Span	TI	$(TI)^2$	(E) (TI)	R^2	Std. Error ($X10^3$)
1	-.0016	--	.0037	.9722	5.32
2	--	--	.0068	.9497	18.07
3	--	--	.0039	.9497	10.32
4	--	--	.0046	.9498	12.21
5	--	--	.0041	.9497	10.83
6	--	--	.0068	.9497	18.07

Total Dose (y_t)

Time Span	TI	$(TI)^2$	(E) (TI)	R^2	Std. Error ($X10^3$)
1	.2668	--	--	.9990	94.13
2	.3868	--	--	.9948	309.43
3	.3130	--	--	.9958	226.67
4	.3435	--	--	.9950	269.77
5	.3133	--	--	.9954	236.54
6	.3902	--	--	.9949	309.39

TABLE 2

Equation Coefficients

Route 2

Dose to Pedestrians (Y_4)

Time Span	TI	$(TI)^2$	(E) (TI)	R^2	Std. Error ($X10^3$)
1	.0015	--	--	.9975	.81
2	.0764	--	--	.9975	42.13
3	.0218	--	--	.9975	12.03
4	.0950	--	--	.9976	51.82
5	.0233	--	--	.9975	13.00
6	.0764	--	--	.9981	36.12

Dose to People in Vehicles (Y_5)

Time Span	TI	$(TI)^2$	(E) (TI)	R^2	Std. Error ($X10^3$)
1	.0028	--	--	.9979	1.45
2	.3694	--	--	.9999	35.63
3	.0875	--	--	.9989	32.12
4	.0917	--	--	1.0000	0
5	.0847	--	--	.9988	32.80
6	.3917	--	--	.9996	53.45

TABLE 2 - Continued

Dose to People in Buildings (y_6)

Time Span	TI	$(TI)^2$	(E) (TI)	R^2	Std. Error ($X10^3$)
1	--	--	.0110	.9811	17.53
2	--	--	.0359	.9806	58.15
3	--	--	.0294	.9771	51.84
4	--	--	.0317	.9794	52.97
5	--	--	.0299	.9777	52.10
6	--	--	.0368	.9842	53.77

Total Dose (y_t)

1	.1668	-.0042	--	.9933	70.51
2	.6386	--	--	.9788	1044.97
3	.2608	--	--	.9278	808.55
4	.3575	--	--	.9473	936.72
5	.2642	--	--	.9250	835.68
6	.6597	--	--	.9798	1052.99

TABLE 3

Equation Coefficients

Route 3

Dose to Pedestrians (y_4)

Time Span	TI	$(TI)^2$	(E) (TI)	R^2	Std. Error ($X10^3$)
1	.0007	--	--	.9975	.22
2	.0357	--	--	.9976	11.45
3	.0102	--	--	.9975	3.31
4	.0445	--	--	.9976	14.19
5	.0109	--	--	.9977	3.37
6	.0357	--	--	.9973	11.95

Dose to People in Vehicles (y_5)

Time Span	TI	$(TI)^2$	(E) (TI)	R^2	Std. Error ($X10^3$)
1	.0312	--	--	.9981	8.77
2	.3238	--	--	.9996	43.64
3	.0698	--	--	.9995	9.80
4	.0705	--	--	.9995	10.24
5	.0686	--	--	.9993	11.95
6	.3429	--	--	1.0000	0

TABLE 3 - Continued

Dose to People in Buildings (y_6)

Time Span	TI	$(TI)^2$	(E) (TI)	R^2	Std. Error ($X10^3$)
1	--	--	.0126	.9492	19.59
2	--	--	.0402	.9490	62.64
3	--	--	.0294	.9528	44.02
4	--	--	.0323	.9529	48.23
5	--	--	.0301	.9526	45.13
6	--	--	.0401	.9470	63.86

Total Dose (y_t)

Time Span	TI	$(TI)^2$	(E) (TI)	R^2	Std. Error ($X10^3$)
1	1.9714	--	--	.9990	410.96
2	2.4786	--	--	.9976	795.07
3	2.1524	--	--	.9976	684.75
4	2.2071	--	--	.9974	733.39
5	2.1571	--	--	.9977	674.24
6	2.4976	--	--	.9975	805.98

TABLE 4

Equation Coefficients

Route 4

Dose to Pedestrians (y_4)

Time Span	TI	$(TI)^2$	(E) (TI)	R^2	Std. Error
1	.2286	--	--	.9974	.08
2	11.9048	--	--	.9980	3.48
3	3.3810	--	--	.9968	1.25
4	14.7619	--	--	.9978	4.49
5	3.6429	--	--	.9973	1.22
6	11.9048	--	--	.9980	3.48

Dose to People in Vehicles (y_5)

Time Span	TI	$(TI)^2$	(E) (TI)	R^2	Std. Error
1	.1643	--	--	.9966	.06
2	107.1429	--	--	.9998	9.43
3	62.6190	--	--	.9999	3.21
4	64.2857	--	--	1.0000	0
5	63.5714	--	--	.9999	3.21
6	114.2857	--	--	.9998	10.69

TABLE 4 - Continued

Dose to People in Buildings (y_6)

Time Span	TI	$(TI)^2$	(E) (TI)	R^2	Std. Error
1	--	--	2.3392	.9737	2.58
2	--	--	16.1344	.9376	27.98
3	--	--	17.5188	.9231	34.00
4	--	--	20.6325	.9194	41.07
5	--	--	18.1690	.9221	35.51
6	--	--	16.1344	.9376	27.98

Total Dose (y_t)

Time Span	TI	$(TI)^2$	(E) (TI)	R^2	Std. Error
1	--	--	2.8147	.9604	3.84
2	135.7738	--	--	.9975	44.28
3	84.2571	--	--	.9934	44.52
4	100.7095	--	--	.9943	49.24
5	85.7238	--	--	.9922	49.38
6	142.9167	--	--	.9978	43.74

TABLE 5

Dose to Handlers (y_1), Person-Rem

Time-Span	Equation	R^2
TS-1, TS-2 & 6 TS-3 & 5, TS-4	$y_1 = 0.5\ (TI)$	1.000

TABLE 6

Dose to Warehousemen (y_2), Person-Rem

Time-Span	Equation	R^2
TS-1, TS-2 & 6 TS-3 & 5, TS-4	$y_2 = 0.9008\ (TI)$	.9981

TABLE 7

Dose to Pedestrians (y_4), Person-Rem

Time-Span	Equation	R^2
TS-1	$y_4 = .507 \times 10^{-6}$ (TI) (PEDD)	.9988
TS-2 & 6	$y_4 = 3.172 \times 10^{-6}$ (TI) (PEDD)	.9987
TS-3 & 5	$y_4 = 1.474 \times 10^{-6}$ (TI) (PEDD)	.9987
TS-4	$y_4 = 1.673 \times 10^{-6}$ (TI) (PEDD)	.9986

TABLE 8

Dose to People in Vehicles (y_5), Person-Rem

Time-Span	Equation	R^2
TS-1	$y_5 = -\ .642 \times 10^{-6}$ (TI) (VSEPDT) $+\ 14.284 \times 10^{-6}$ (TI) (TFCNT)	.9967
TS-2 & 6	$y_5 = 3.444 + .2438$ (TI) $-\ .1136$ (VSEPDT) $+\ 756.296 \times 10^{-6}$ (VSEPDT)^2 $+\ 144.212 \times 10^{-6}$ (TI) (TFCNT)	.8504
TS-3 & 5	$y^5 = .319 + .0539$ (TI) $+\ 175.671 \times 10^{-6}$ (TI) (TFCNT) $-\ 6.263 \times 10^{-6}$ (VSEPDT) (TFCNT)	.5127
TS-4	$y_5 = 2.611 - 73.468 \times 10^{-3}$ (VSEPDT) $+\ 467.558 \times 10^{-6}$ (VSEPDT)^2 $+\ 395.525$ (TI) (TFCNT) $-\ 6.913 \times 10^{-6}$ (VSEPDT) (TFCNT)	.6810

TABLE 9

Dose to People in Buildings (y_6), Person-Rem

Time-Span	Equation	R^2
TS-1	$y_6 = -\ .008 + 134.641 \times 10^{-6}\ (NFLR)^2$	.9957
	$+\ 4979 \times 10^{-6}\ (E)\ (TI)$	
	$+\ 1.09 \times 10^{-6}\ (E)\ (PD)$	
	$-\ 2311 \times 10^{-6}\ (TI)\ (NFLR)$	
	$+\ .105 \times 10^{-6}\ (TI)\ (PD)$	
	$-\ 273 \times 10^{-6}\ (TI)\ (NFLR)$	
	$-\ .060 \times 10^{-6}\ (PD)\ (NFLR)$	
TS-2 & 6	$y_6 = -\ .075 + 14456 \times 10^{-6}\ (E)\ (TI)$	.9574
	$+\ 5.112 \times 10^{-6}\ (E)\ (PD)$	
	$+\ .319 \times 10^{-6}\ (TI)\ (PD)$	
	$-\ .255 \times 10^{-6}\ (PD)\ (NFLR)$	
TS-3 & 5	$y_6 = -\ .006 + 6351 \times 10^{-6}\ (E)\ (TI)$	.9192
	$+\ .\text{[illegible]}20 \times 10^{-6}\ (TI)\ (PD)$	
	$+\ .319 \times 10^{-5}\ (TI)\ (SHOPED)$	
	$-\ 338 \times 10^{-6}\ (TI)\ (NFLR)$	
TS-4	$y_6 = -\ .007 + 7358 \times 10^{-6}\ (E)\ (TI)$	.91929
	$+\ .371 \times 10^{-6}\ (TI)\ (PD)$	
	$+\ .370 \times 10^{-6}\ (TI)\ (SHOPED)$	
	$-\ 391 \times 10^{-6}\ (TI)\ (NFLR)$	

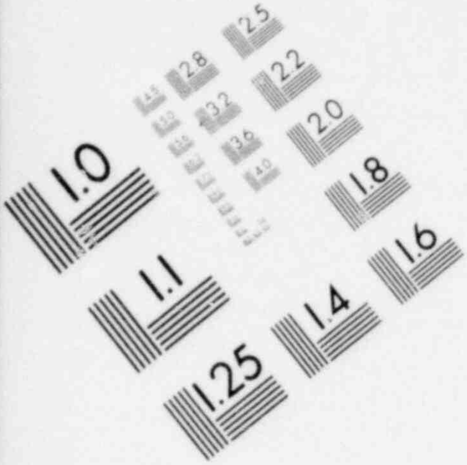
TABLE 10

Total Dose (y_t), Person-Rem

Time-Span	Equation	R^2
TS-1	$y_t = .759 + 1.4690\ (TI)$	.9986
TS-2 & 6	$y_t = 2.796 + 2.0484\ (TI)$	.9798
TS-3 & 4	$y_t = 2.151 + 1.7256\ (TI)$	.9832
TS-4	$y_t = 2.498 + 1.8465\ (TI)$	.9776

IMAGE EVALUATION
TEST TARGET (MT-3)

6"



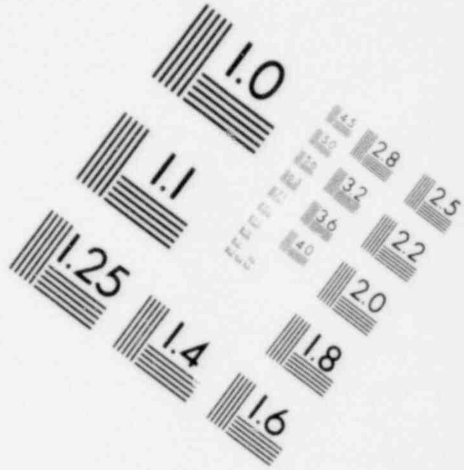
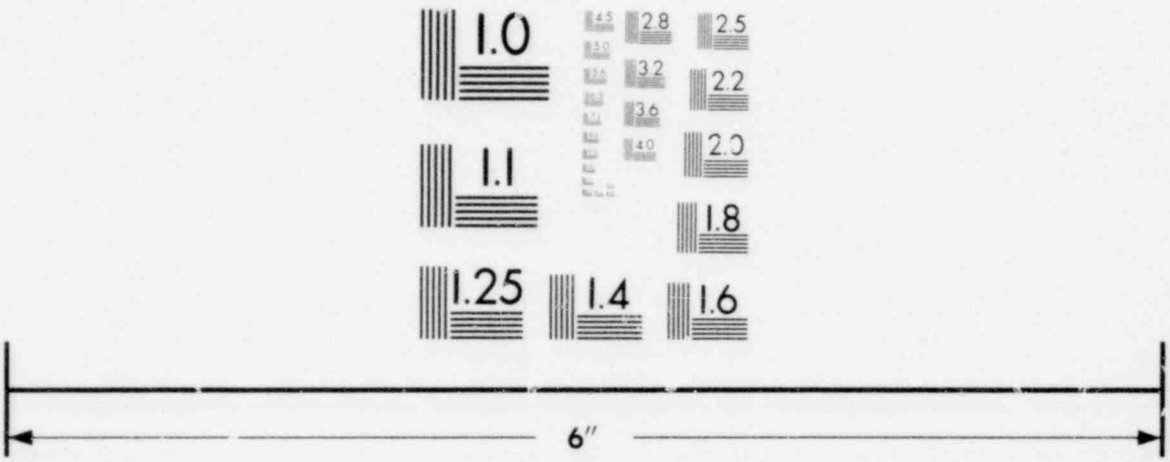
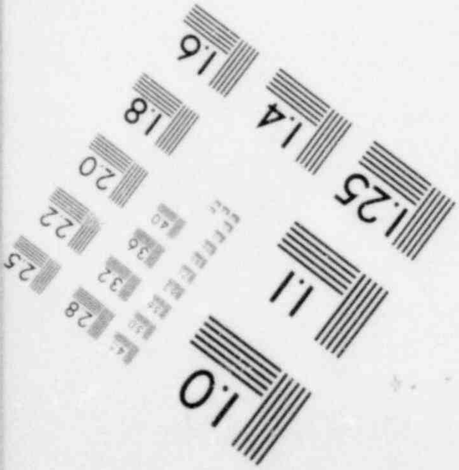


IMAGE EVALUATION TEST TARGET (MT-3)





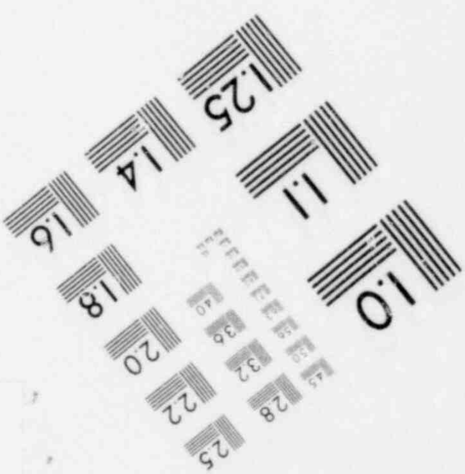


TABLE 11

ACCIDENT-FREE MODEL DATA USED FOR SENSITIVITY ANALYSIS

TIME SPAN 1

Y(1)	Y(2)	Y(3)	Y(4)	Y(5)	Y(6)	Y(T)	E	TI	VSFPDT	PEDD	TECNT	PD	SHOPED	NFLR
1.650E+00	2.914E+00	9.506E-01	3.869E-03	1.820E-03	6.253E-03	5.534E+00	.7	3.3	107.90	2359	45.0	15391	0	8
5.350E+00	9.823E+00	1.380E+00	1.303E-02	6.155E-03	3.608E-02	1.664E+01	1.1	10.7	107.90	2359	45.0	15391	0	8
5.350E+00	9.823E+00	1.380E+00	1.303E-02	1.946E-02	3.608E-02	1.664E+01	1.1	10.7	151.70	2359	134.0	15391	0	8
1.650E+00	2.914E+00	9.506E-01	3.869E-03	5.770E-03	6.253E-03	5.534E+00	.7	3.3	151.70	2359	134.0	15391	0	8
5.350E+00	9.823E+00	1.380E+00	2.654E-02	6.155E-03	3.608E-02	1.664E+01	1.1	10.7	151.70	4807	45.0	15391	0	8
1.650E+00	2.914E+00	9.506E-01	7.883E-03	1.820E-03	6.253E-03	5.534E+00	.7	3.3	151.70	4807	45.0	15391	0	8
1.650E+00	2.914E+00	9.506E-01	7.883E-03	6.090E-03	6.253E-03	5.544E+00	.7	3.3	107.90	4807	134.0	15391	0	8
5.350E+00	9.823E+00	1.380E+00	2.654E-02	2.050E-02	3.608E-02	1.664E+01	1.1	10.7	107.90	4807	134.0	15391	0	8
5.350E+00	9.450E+00	1.380E+00	1.254E-02	1.871E-02	6.432E-02	1.630E+01	.7	10.7	151.70	2359	134.0	48831	0	8
1.650E+00	3.030E+00	9.565E-01	4.017E-03	6.003E-03	3.531E-02	5.680E+00	1.1	3.3	151.70	2359	134.0	48831	0	8
1.650E+00	3.030E+00	9.565E-01	4.017E-03	1.898E-03	3.531E-02	5.670E+00	1.1	3.3	107.90	2359	45.0	48831	0	8
5.350E+00	9.450E+00	1.380E+00	1.254E-02	5.901E-03	6.432E-02	1.630E+01	.7	10.7	107.90	2359	45.0	48831	0	8
1.650E+00	3.030E+00	9.565E-01	8.187E-03	6.323E-03	3.531E-02	5.680E+00	1.1	3.3	107.90	4807	134.0	48831	0	8
5.350E+00	9.450E+00	1.380E+00	2.556E-02	1.975E-02	6.432E-02	1.630E+01	.7	10.7	107.90	4807	134.0	48831	0	8
5.350E+00	9.450E+00	1.380E+00	2.556E-02	5.901E-03	6.432E-02	1.630E+01	.7	10.7	151.70	4807	45.0	48831	0	8
1.650E+00	3.030E+00	9.565E-01	8.187E-03	1.898E-03	3.531E-02	5.680E+00	1.1	3.3	151.70	4807	45.0	48831	0	8
1.650E+00	3.030E+00	9.565E-01	4.017E-03	1.898E-03	1.113E-02	5.650E+00	1.1	3.3	151.70	2359	45.0	15391	0	8
5.350E+00	9.450E+00	1.380E+00	1.254E-02	5.901E-03	2.027E-02	1.620E+01	.7	10.7	151.70	2359	45.0	15391	0	8
5.350E+00	9.450E+00	1.380E+00	1.254E-02	1.975E-02	2.027E-02	1.620E+01	.7	10.7	107.90	2359	134.0	15391	0	8
1.650E+00	3.030E+00	9.565E-01	4.017E-03	6.323E-03	1.113E-02	5.650E+00	1.1	3.3	107.90	2359	134.0	15391	0	8
5.350E+00	9.450E+00	1.380E+00	2.556E-02	5.901E-03	2.027E-02	1.620E+01	.7	10.7	107.90	4807	45.0	15391	0	8
1.650E+00	3.030E+00	9.565E-01	8.187E-03	1.898E-03	1.113E-02	5.650E+00	1.1	3.3	107.90	4807	45.0	15391	0	8
1.650E+00	3.030E+00	9.565E-01	8.187E-03	6.003E-03	1.113E-02	5.660E+00	1.1	3.3	151.70	4807	134.0	15391	0	8
5.350E+00	9.450E+00	1.380E+00	2.556E-02	1.871E-02	2.027E-02	1.620E+01	.7	10.7	151.70	4807	134.0	15391	0	8
5.350E+00	9.823E+00	1.380E+00	1.303E-02	2.050E-02	1.145E-01	1.674E+01	1.1	10.7	107.90	2359	134.0	48831	0	8
1.650E+00	2.914E+00	9.506E-01	3.869E-03	6.090E-03	1.984E-02	5.544E+00	.7	3.3	107.90	2359	134.0	48831	0	8
1.650E+00	2.914E+00	9.506E-01	3.869E-03	1.820E-03	1.984E-02	5.544E+00	.7	3.3	151.70	2359	45.0	48831	0	8
5.350E+00	9.823E+00	1.380E+00	1.303E-02	6.155E-03	1.145E-01	1.664E+01	1.1	10.7	151.70	2359	45.0	48831	0	8
1.650E+00	2.914E+00	9.506E-01	7.883E-03	5.770E-03	1.984E-02	5.554E+00	.7	3.3	151.70	4807	134.0	48831	0	8
5.350E+00	9.823E+00	1.380E+00	2.654E-02	1.946E-02	1.145E-01	1.674E+01	1.1	10.7	151.70	4807	134.0	48831	0	8
5.350E+00	9.823E+00	1.380E+00	2.654E-02	6.155E-03	1.145E-01	1.674E+01	1.1	10.7	107.90	4807	45.0	48831	0	8
1.650E+00	2.914E+00	9.506E-01	7.883E-03	1.820E-03	1.984E-02	5.544E+00	.7	3.3	107.90	4807	45.0	48831	0	8
5.350E+00	9.450E+00	1.380E+00	1.254E-02	5.901E-03	7.584E-03	1.620E+01	.7	10.7	107.90	2359	45.0	15391	0	22
1.650E+00	3.030E+00	9.565E-01	4.017E-03	1.898E-03	4.170E-03	5.640E+00	1.1	3.3	107.90	2359	45.0	15391	0	22
1.650E+00	3.030E+00	9.565E-01	4.017E-03	6.003E-03	4.170E-03	5.650E+00	1.1	3.3	151.70	2359	134.0	15391	0	22
5.350E+00	4.450E+00	1.380E+00	1.254E-02	1.871E-02	7.584E-03	1.620E+01	.7	10.7	151.70	2359	134.0	15391	0	22
1.650E+00	3.030E+00	9.565E-01	8.187E-03	1.898E-03	4.170E-03	5.650E+00	1.1	3.3	151.70	4807	45.0	15391	0	22
5.350E+00	9.450E+00	1.380E+00	2.556E-02	5.901E-03	7.584E-03	1.620E+01	.7	10.7	151.70	4807	45.0	15391	0	22
5.350E+00	9.450E+00	1.380E+00	2.556E-02	1.975E-02	7.584E-03	1.620E+01	.7	10.7	107.90	4807	134.0	15391	0	22
1.650E+00	3.030E+00	9.565E-01	8.187E-03	6.323E-03	4.170E-03	5.650E+00	1.1	3.3	107.90	4807	134.0	15391	0	22
1.650E+00	2.914E+00	9.506E-01	3.869E-03	5.770E-03	7.421E-03	5.534E+00	.7	3.3	151.70	2359	134.0	48831	0	22
5.350E+00	9.823E+00	1.380E+00	1.303E-02	1.946E-02	4.290E-02	1.564E+01	1.1	10.7	151.70	2359	134.0	48831	0	22
5.350E+00	9.823E+00	1.380E+00	1.303E-02	6.155E-03	4.290E-02	1.664E+01	1.1	10.7	107.90	2359	45.0	48831	0	22
1.650E+00	2.914E+00	9.506E-01	3.869E-03	1.820E-03	7.421E-03	5.534E+00	.7	3.3	107.90	2359	45.0	48831	0	22
5.350E+00	9.823E+00	1.380E+00	2.654E-02	2.050E-02	4.290E-02	1.664E+01	1.1	10.7	107.90	4807	134.0	48831	0	22
1.650E+00	2.914E+00	9.506E-01	7.883E-03	6.090E-03	7.421E-03	5.544E+00	.7	3.3	107.90	4807	134.0	48831	0	22
1.650E+00	2.914E+00	9.506E-01	7.883E-03	1.820E-03	7.421E-03	5.534E+00	.7	3.3	151.70	4807	45.0	48831	0	22
5.350E+00	9.823E+00	1.380E+00	2.654E-02	6.155E-03	4.290E-02	1.664E+01	1.1	10.7	151.70	4807	45.0	48831	0	22
5.350E+00	9.823E+00	1.380E+00	1.303E-02	6.155E-03	1.352E-02	1.654E+01	1.1	10.7	151.70	2359	45.0	15391	0	22

TABLE 11 (CONT'D)

ACCIDENT-FREE MODEL DATA USED FOR SENSITIVITY ANALYSIS

TIME SPAN 1

Y(1)	Y(2)	Y(3)	Y(4)	Y(5)	Y(6)	Y(T)	F	TI	VSFPDT	PFDC	TECHT	PD	SHOPFD	NFLR
1.650E+00	2.914E+00	9.506E-01	3.869E-03	1.820E-03	2.339E-03	5.524E+00	.7	3.3	151.70	2359	45.0	15391	0	22
1.650E+00	2.914E+00	9.506E-01	3.869E-03	6.090E-03	2.339E-03	5.534E+00	.7	3.3	107.90	2359	134.0	15391	0	22
5.350E+00	9.823E+00	1.380E+00	1.303E-02	2.050E-02	1.352E-02	1.664E+01	1.1	10.7	107.90	2359	134.0	15391	0	22
1.650E+00	2.914E+00	9.506E-01	7.883E-03	1.820E-03	2.339E-03	5.534E+00	.7	3.3	107.90	4807	45.0	15391	0	22
5.350E+00	9.823E+00	1.380E+00	2.554E-02	5.155E-03	1.352E-02	1.664E+01	1.1	10.7	107.90	4807	45.0	15391	0	22
5.350E+00	9.823E+00	1.380E+00	2.654E-02	1.946E-02	1.352E-02	1.664E+01	1.1	10.7	151.70	4807	134.0	15391	0	22
1.650E+00	2.914E+00	9.506E-01	7.883E-03	5.770E-03	2.339E-03	5.534E+00	.7	3.3	151.70	4807	134.0	15391	0	22
1.650E+00	3.030E+00	9.565E-01	4.017E-03	6.323E-03	1.323E-02	5.663E+00	1.1	3.3	107.90	2359	134.0	48831	0	22
5.350E+00	9.450E+00	1.380E+00	1.254E-02	1.975E-02	2.406E-02	1.620E+01	.7	10.7	107.90	2359	134.0	48831	0	22
5.350E+00	9.450E+00	1.380E+00	1.254E-02	5.901E-03	2.406E-02	1.620E+01	.7	10.7	151.70	2359	45.0	48831	0	22
1.650E+00	3.030E+00	9.565E-01	4.017E-03	1.898E-03	1.323E-02	5.550E+00	1.1	3.3	151.70	2359	45.0	48831	0	22
5.350E+00	9.450E+00	1.380E+00	2.556E-02	1.871E-02	2.406E-02	1.620E+01	.7	10.7	151.70	4807	134.0	48831	0	22
1.650E+00	3.030E+00	9.565E-01	8.187E-03	6.003E-03	1.323E-02	5.663E+00	1.1	3.3	151.70	4807	134.0	48831	0	22
1.650E+00	3.030E+00	9.565E-01	8.187E-03	1.898E-03	1.323E-02	5.660E+00	1.1	3.3	107.90	4807	45.0	48831	0	22
5.350E+00	9.450E+00	1.380E+00	2.556E-02	5.901E-03	2.406E-02	1.620E+01	.7	10.7	107.90	4807	45.0	48831	0	22
3.500E+00	6.318E+00	1.380E+00	1.273E-02	8.863E-03	2.223E-02	1.124E+01	.9	7.0	129.80	3583	89.5	32111	0	15
3.500E+00	6.017E+00	1.380E+00	1.214E-02	8.457E-03	5.030E-03	1.093E+01	.5	7.0	129.80	3583	89.5	32111	0	15
3.500E+00	6.511E+00	1.380E+00	1.311E-02	9.126E-03	3.181E-02	1.143E+01	1.3	7.0	129.80	3583	89.5	32111	0	15
0.	0.	0.	0.	0.	0.	0.	.9	3.0	129.80	3583	89.5	32111	0	15
7.000E+00	1.264E+01	1.380E+00	2.546E-02	1.773E-02	4.446E-02	2.104E+01	.9	14.0	129.80	3583	89.5	32111	0	15
3.500E+00	6.318E+00	1.380E+00	1.273E-02	9.924E-03	2.223E-02	1.124E+01	.9	7.0	88.50	3583	89.5	32111	0	15
3.500E+00	6.318E+00	1.380E+00	1.273E-02	8.451E-03	2.223E-02	1.124E+01	.9	7.0	171.10	3583	89.5	32111	0	15
3.500E+00	6.318E+00	1.380E+00	4.530E-03	8.863E-03	2.223E-02	1.123E+01	.9	7.0	129.80	1275	89.5	32111	0	15
3.500E+00	6.318E+00	1.380E+00	2.093E-02	8.863E-03	2.223E-02	1.125E+01	.9	7.0	129.80	5891	89.5	32111	0	15
3.500E+00	6.318E+00	1.380E+00	1.273E-02	4.392E-04	2.223E-02	1.123E+01	.9	7.0	129.80	3583	5.0	32111	0	15
3.500E+00	6.318E+00	1.380E+00	1.273E-02	1.628E-02	2.223E-02	1.125E+01	.9	7.0	129.80	3583	174.0	32111	0	15
3.500E+00	6.318E+00	1.380E+00	1.273E-02	8.863E-03	4.105E-04	1.122E+01	.9	7.0	129.80	3583	89.5	597	0	15
3.500E+00	6.318E+00	1.380E+00	1.273E-02	8.863E-03	4.405E-02	1.126E+01	.9	7.0	129.80	3583	89.5	63629	0	15
3.500E+00	6.318E+00	1.380E+00	1.273E-02	8.863E-03	1.003E-01	1.132E+01	.9	7.0	129.80	3583	89.5	32111	0	1
3.500E+00	6.318E+00	1.380E+00	1.273E-02	8.863E-03	1.158E-02	1.123E+01	.9	7.0	129.80	3583	89.5	32111	0	29

TABLE 12

ACCIDENT-FREE MODEL DATA USED FOR SENSITIVITY ANALYSIS

TIME SPANS 2 AND 6

Y(1)	Y(2)	Y(3)	Y(4)	Y(5)	Y(6)	Y(T)	E	TI	VSFPDT	PFOD	TFCNT	PD	SHOPED	NFLR
1.800E+00	3.179E+00	3.393E+00	2.294E-01	1.150E+00	4.566E-02	9.799E+00	.7	3.6	36.10	20477	400.0	26974	4517	8
5.200E+00	9.548E+00	4.514E+00	6.883E-01	3.337E+00	2.348E-01	2.357E+01	1.1	10.4	36.10	20477	400.0	26974	4517	8
1.800E+00	3.179E+00	3.393E+00	4.428E-01	1.150E+00	4.566E-02	1.001E+01	.7	3.6	36.10	39523	400.0	26974	4517	8
5.200E+00	9.548E+00	4.514E+00	1.328E+00	3.337E+00	2.348E-01	2.417E+01	1.1	10.4	36.10	39523	400.0	26974	4517	8
1.800E+00	3.179E+00	3.393E+00	2.294E-01	1.491E+00	4.566E-02	1.014E+01	.7	3.6	36.10	20477	1084.0	26974	4517	8
5.200E+00	9.548E+00	4.514E+00	6.883E-01	4.348E+00	2.348E-01	2.457E+01	1.1	10.4	36.10	20477	1084.0	26974	4517	8
1.800E+00	3.179E+00	3.393E+00	4.428E-01	1.491E+00	4.566E-02	1.036E+01	.7	3.6	36.10	39523	1084.0	26974	4517	8
5.200E+00	9.548E+00	4.514E+00	1.328E+00	4.348E+00	2.348E-01	2.517E+01	1.1	10.4	36.10	39523	1084.0	26974	4517	8
1.800E+00	3.179E+00	3.393E+00	4.428E-01	1.044E+00	1.201E-01	9.979E+00	.7	3.6	105.10	39523	400.0	78310	4517	8
5.200E+00	9.548E+00	4.514E+00	1.328E+00	3.032E+00	6.174E-01	2.427E+01	1.1	10.4	105.10	39523	400.0	78310	4517	8
1.800E+00	3.179E+00	3.393E+00	4.428E-01	1.491E+00	1.328E-01	1.044E+01	.7	3.6	36.10	39523	1084.0	78310	13265	8
5.200E+00	9.548E+00	4.514E+00	1.328E+00	4.348E+00	6.827E-01	2.567E+01	1.1	10.4	36.10	39523	1084.0	78310	13265	8
1.800E+00	3.179E+00	3.393E+00	2.294E-01	1.150E+00	1.201E-01	9.879E+00	.7	3.6	36.10	20477	400.0	78310	4517	8
5.200E+00	9.548E+00	4.514E+00	6.883E-01	3.337E+00	6.174E-01	2.387E+01	1.1	10.4	36.10	20477	400.0	78310	4517	8
1.800E+00	3.179E+00	3.393E+00	4.428E-01	1.150E+00	1.201E-01	1.009E+01	.7	3.6	36.10	39523	400.0	78310	4517	8
5.200E+00	9.548E+00	4.514E+00	1.328E+00	3.337E+00	6.174E-01	2.457E+01	1.1	10.4	36.10	39523	400.0	78310	4517	8
1.800E+00	3.179E+00	3.393E+00	2.294E-01	1.491E+00	1.201E-01	1.022E+01	.7	3.6	36.10	20477	1084.0	78310	4517	8
5.200E+00	9.548E+00	4.514E+00	6.883E-01	4.348E+00	6.174E-01	2.487E+01	1.1	10.4	36.10	20477	1084.0	78310	4517	8
1.800E+00	3.179E+00	3.393E+00	4.428E-01	1.491E+00	1.201E-01	1.043E+01	.7	3.6	36.10	39523	1084.0	78310	4517	8
5.200E+00	9.548E+00	4.514E+00	1.328E+00	4.348E+00	6.174E-01	2.557E+01	1.1	10.4	36.10	39523	1084.0	78310	4517	8
1.800E+00	3.179E+00	3.393E+00	2.294E-01	1.044E+00	4.566E-02	9.699E+00	.7	3.6	105.10	20477	400.0	26974	4517	8
5.200E+00	9.548E+00	4.514E+00	6.883E-01	3.032E+00	2.348E-01	2.317E+01	1.1	10.4	105.10	20477	400.0	26974	4517	8
1.800E+00	3.179E+00	3.393E+00	4.428E-01	1.044E+00	4.566E-02	9.909E+00	.7	3.6	105.10	39523	400.0	26974	4517	8
5.200E+00	9.548E+00	4.514E+00	1.328E+00	3.032E+00	2.348E-01	2.387E+01	1.1	10.4	105.10	39523	400.0	26974	4517	8
1.800E+00	3.179E+00	3.393E+00	2.294E-01	1.371E+00	4.566E-02	1.002E+01	.7	3.6	105.10	20477	1084.0	26974	4517	8
5.200E+00	9.548E+00	4.514E+00	6.883E-01	4.002E+00	2.348E-01	2.417E+01	1.1	10.4	105.10	20477	1084.0	26974	4517	8
1.800E+00	3.179E+00	3.393E+00	4.428E-01	1.371E+00	4.566E-02	1.024E+01	.7	3.6	105.10	39523	1084.0	26974	4517	8
5.200E+00	9.548E+00	4.514E+00	1.328E+00	4.002E+00	2.348E-01	2.487E+01	1.1	10.4	105.10	39523	1084.0	26974	4517	8
1.800E+00	3.179E+00	3.393E+00	2.294E-01	1.044E+00	1.201E-01	9.769E+00	.7	3.6	105.10	20477	400.0	78310	4517	8
5.200E+00	9.548E+00	4.514E+00	6.883E-01	3.032E+00	6.174E-01	2.357E+01	1.1	10.4	105.10	20477	400.0	78310	4517	8
1.800E+00	3.179E+00	3.393E+00	2.294E-01	1.371E+00	1.201E-01	1.013E+01	.7	3.6	105.10	20477	1084.0	78310	4517	8
5.200E+00	9.548E+00	4.514E+00	6.883E-01	4.002E+00	6.174E-01	2.457E+01	1.1	10.4	105.10	20477	1084.0	78310	4517	8
1.800E+00	3.179E+00	3.393E+00	4.428E-01	1.371E+00	1.201E-01	1.031E+01	.7	3.6	105.10	39523	1084.0	78310	4517	8
5.200E+00	9.548E+00	4.514E+00	1.328E+00	4.002E+00	6.174E-01	2.517E+01	1.1	10.4	105.10	39523	1084.0	78310	4517	8
1.800E+00	3.179E+00	3.393E+00	2.294E-01	1.150E+00	5.834E-02	9.809E+00	.7	3.6	36.10	20477	400.0	26974	13265	8
5.200E+00	9.548E+00	4.514E+00	6.883E-01	3.337E+00	3.000E-01	2.357E+01	1.1	10.4	36.10	20477	400.0	26974	13265	8
1.800E+00	3.179E+00	3.393E+00	4.428E-01	1.150E+00	5.834E-02	1.003E+01	.7	3.6	36.10	39523	400.0	26974	13265	8
5.200E+00	9.548E+00	4.514E+00	1.328E+00	3.337E+00	3.000E-01	2.427E+01	1.1	10.4	36.10	39523	400.0	26974	13265	8
1.800E+00	3.179E+00	3.393E+00	2.294E-01	1.491E+00	5.834E-02	1.016E+01	.7	3.6	36.10	20477	1084.0	26974	13265	8
5.200E+00	9.548E+00	4.514E+00	6.883E-01	4.348E+00	3.000E-01	2.457E+01	1.1	10.4	36.10	20477	1084.0	26974	13265	8
1.800E+00	3.179E+00	3.393E+00	4.428E-01	1.491E+00	5.834E-02	1.037E+01	.7	3.6	36.10	39523	1084.0	26974	13265	8
5.200E+00	9.548E+00	4.514E+00	1.328E+00	4.348E+00	3.000E-01	2.527E+01	1.1	10.4	36.10	39523	1084.0	26974	13265	8
1.800E+00	3.179E+00	3.393E+00	2.294E-01	1.150E+00	1.328E-01	9.889E+00	.7	3.6	36.10	20477	400.0	78310	13265	8
5.200E+00	9.548E+00	4.514E+00	6.883E-01	3.337E+00	6.827E-01	2.397E+01	1.1	10.4	36.10	20477	400.0	78310	13265	8
1.800E+00	3.179E+00	3.393E+00	4.428E-01	1.150E+00	1.328E-01	1.013E+01	.7	3.6	36.10	39523	400.0	78310	13265	8
5.200E+00	9.548E+00	4.514E+00	1.328E+00	3.337E+00	6.827E-01	2.457E+01	1.1	10.4	36.10	39523	400.0	78310	13265	8
1.800E+00	3.179E+00	3.393E+00	2.294E-01	1.491E+00	1.328E-01	1.023E+01	.7	3.6	36.10	20477	1084.0	78310	13265	8
5.200E+00	9.548E+00	4.514E+00	6.883E-01	4.348E+00	6.827E-01	2.497E+01	1.1	10.4	36.10	20477	1084.0	78310	13265	8
1.800E+00	3.179E+00	3.393E+00	2.294E-01	1.044E+00	5.834E-02	9.709E+00	.7	3.6	105.10	20477	400.0	26974	13265	8

TABLE 12 (CONT'D)

ACCIDENT-FREE MODEL DATA USED FOR SENSITIVITY ANALYSIS

TIME SPANS 2 AND 6

Y(1)	Y(2)	Y(3)	Y(4)	Y(5)	Y(6)	Y(7)	E	TI	VSFPDT	PFDD	IFCNT	PD	SHOPED	NFLR
5.200E+00	9.548E+00	4.514E+00	6.883E-01	3.032E+00	3.000E-01	2.327E+01	1.1	10.4	105.10	20477	400.0	26974	13265	8
1.800E+00	3.179E+00	3.393E+00	4.428E-01	1.044E+00	5.834E-02	9.319E+00	.7	3.6	105.10	39523	400.0	26974	13265	8
5.200E+00	9.548E+00	4.514E+00	1.328E+00	3.032E+00	3.000E-01	2.397E+01	1.1	10.4	105.10	39523	400.0	26974	13265	8
1.800E+00	3.179E+00	3.393E+00	2.294E-01	1.371E+00	5.834E-02	1.004E+01	.7	3.6	105.10	20477	1084.0	26974	13265	8
5.200E+00	9.548E+00	4.514E+00	6.883E-01	4.002E+00	3.000E-01	2.427E+01	1.1	10.4	105.10	20477	1084.0	26974	13265	8
1.800E+00	3.179E+00	3.393E+00	4.428E-01	1.371E+00	5.834E-02	1.025E+01	.7	3.6	105.10	39523	1084.0	26974	13265	8
5.200E+00	9.548E+00	4.514E+00	1.328E+00	4.002E+00	3.000E-01	2.487E+01	1.1	10.4	105.10	39523	1084.0	26974	13265	8
1.800E+00	3.179E+00	3.393E+00	2.294E-01	1.044E+00	1.328E-01	9.773E+00	.7	3.6	105.10	20477	400.0	78310	13265	8
5.200E+00	9.548E+00	4.514E+00	6.883E-01	3.032E+00	6.827E-01	2.367E+01	1.1	10.4	105.10	20477	400.0	78310	13265	8
1.800E+00	3.179E+00	3.393E+00	4.428E-01	1.044E+00	1.328E-01	9.999E+00	.7	3.6	105.10	39523	400.0	78310	13265	8
5.200E+00	9.548E+00	4.514E+00	1.328E+00	3.032E+00	6.827E-01	2.427E+01	1.1	10.4	105.10	39523	400.0	78310	13265	8
1.800E+00	3.179E+00	3.393E+00	2.294E-01	1.371E+00	1.328E-01	1.011E+01	.7	3.6	105.10	20477	1084.0	78310	13265	8
5.200E+00	9.548E+00	4.514E+00	6.883E-01	4.002E+00	6.827E-01	2.467E+01	1.1	10.4	105.10	20477	1084.0	78310	13265	8
1.800E+00	3.179E+00	3.393E+00	4.428E-01	1.371E+00	1.328E-01	1.032E+01	.7	3.6	105.10	39523	1084.0	78310	13265	8
5.200E+00	9.548E+00	4.514E+00	1.328E+00	4.002E+00	6.827E-01	2.527E+01	1.1	10.4	105.10	39523	1084.0	78310	13265	8
5.200E+00	9.185E+00	4.514E+00	6.628E-01	3.323E+00	4.934E-02	2.294E+01	.7	10.4	36.10	20477	400.0	26974	4517	22
1.800E+00	3.305E+00	3.414E+00	2.382E-01	1.155E+00	3.045E-02	9.345E+00	1.1	3.6	36.10	20477	400.0	26974	4517	22
5.200E+00	9.185E+00	4.514E+00	1.279E+00	3.323E+00	4.934E-02	2.354E+01	.7	10.4	36.10	39523	400.0	26974	4517	22
1.800E+00	3.305E+00	3.414E+00	4.598E-01	1.155E+00	3.045E-02	1.017E+01	1.1	3.6	36.10	39523	400.0	26974	4517	22
5.200E+00	9.185E+00	4.514E+00	6.628E-01	4.307E+00	4.934E-02	2.394E+01	.7	10.4	36.10	20477	1084.0	26974	4517	22
1.800E+00	3.305E+00	3.414E+00	2.382E-01	1.505E+00	3.045E-02	1.030E+01	1.1	3.6	36.10	20477	1084.0	26974	4517	22
5.200E+00	9.185E+00	4.514E+00	1.279E+00	4.307E+00	4.934E-02	2.454E+01	.7	10.4	36.10	39523	1084.0	26974	4517	22
1.800E+00	3.305E+00	3.414E+00	4.598E-01	1.505E+00	3.045E-02	1.052E+01	1.1	3.6	36.10	39523	1084.0	26974	4517	22
5.200E+00	9.185E+00	4.514E+00	1.279E+00	3.017E+00	1.298E-01	2.334E+01	.7	10.4	105.10	39523	400.0	78310	4517	22
1.800E+00	3.305E+00	3.414E+00	4.598E-01	1.050E+00	8.009E-02	1.011E+01	1.1	3.6	105.10	39523	400.0	78310	4517	22
5.200E+00	9.185E+00	4.514E+00	1.279E+00	4.307E+00	1.435E-01	2.464E+01	.7	10.4	36.10	39523	1084.0	78310	13265	22
1.800E+00	3.305E+00	3.414E+00	4.598E-01	1.505E+00	8.855E-02	1.058E+01	1.1	3.6	36.10	39523	1084.0	78310	13265	22
5.200E+00	9.185E+00	4.514E+00	6.628E-01	3.323E+00	1.298E-01	2.304E+01	.7	10.4	36.10	20477	400.0	78310	4517	22
1.800E+00	3.305E+00	3.414E+00	2.382E-01	1.155E+00	8.009E-02	9.995E+00	1.1	3.6	36.10	20477	400.0	78310	4517	22
5.200E+00	9.185E+00	4.514E+00	1.279E+00	3.323E+00	1.298E-01	2.364E+01	.7	10.4	36.10	3957	400.0	78310	4517	22
1.800E+00	3.305E+00	3.414E+00	4.598E-01	1.155E+00	8.009E-02	1.022E+01	1.1	3.6	36.10	395 3	400.0	78310	4517	22
5.200E+00	9.185E+00	4.514E+00	6.628E-01	4.307E+00	1.298E-01	2.404E+01	.7	10.4	36.10	20477	1084.0	78310	4517	22
1.800E+00	3.305E+00	3.414E+00	2.382E-01	1.505E+00	8.009E-02	1.035E+01	1.1	3.6	36.10	20477	1084.0	78310	4517	22
5.200E+00	9.185E+00	4.514E+00	1.279E+00	4.307E+00	1.298E-01	2.464E+01	.7	10.4	36.10	39523	1084.0	78310	4517	22
1.800E+00	3.305E+00	3.414E+00	4.598E-01	1.505E+00	8.009E-02	1.057E+01	1.1	3.6	36.10	39523	1084.0	78310	4517	22
5.200E+00	9.185E+00	4.514E+00	6.628E-01	3.017E+00	4.934E-02	2.264E+01	.7	10.4	105.10	20477	400.0	26974	4517	22
1.800E+00	3.305E+00	3.414E+00	2.382E-01	1.050E+00	3.045E-02	9.835E+00	1.1	3.6	105.10	20477	400.0	26974	4517	22
5.200E+00	9.185E+00	4.514E+00	1.279E+00	3.017E+00	4.934E-02	2.324E+01	.7	10.4	105.10	39523	400.0	26974	4517	22
1.800E+00	3.305E+00	3.414E+00	4.598E-01	1.050E+00	3.045E-02	1.306E+01	1.1	3.6	105.10	39523	400.0	26974	4517	22
5.200E+00	9.185E+00	4.514E+00	6.628E-01	3.962E+00	4.934E-02	2.354E+01	.7	10.4	105.10	20477	1084.0	26974	4517	22
1.800E+00	3.305E+00	3.414E+00	2.382E-01	1.385E+00	3.045E-02	1.618E+01	1.1	3.6	105.10	20477	1084.0	26974	4517	22
5.200E+00	9.185E+00	4.514E+00	1.279E+00	3.962E+00	4.934E-02	2.424E+01	.7	10.4	105.10	39523	1084.0	26974	4517	22
1.800E+00	3.305E+00	3.414E+00	4.598E-01	1.385E+00	3.045E-02	1.040E+01	1.1	3.6	105.10	39523	1084.0	26974	4517	22
5.200E+00	9.185E+00	4.514E+00	6.628E-01	3.017E+00	1.298E-01	2.274E+01	.7	10.4	105.10	20477	400.0	78310	4517	22
1.800E+00	3.305E+00	3.414E+00	2.382E-01	1.050E+00	8.009E-02	9.885E+00	1.1	3.6	105.10	20477	400.0	78310	4517	22
5.200E+00	9.185E+00	4.514E+00	6.628E-01	3.962E+00	1.298E-01	2.364E+01	.7	10.4	105.10	20477	1084.0	78310	4517	22
1.800E+00	3.305E+00	3.414E+00	2.382E-01	1.385E+00	8.009E-02	1.023E+01	1.1	3.6	105.10	20477	1084.0	78310	4517	22
5.200E+00	9.185E+00	4.514E+00	1.279E+00	3.962E+00	1.298E-01	2.424E+01	.7	10.4	105.10	39523	1084.0	78310	4517	22
1.800E+00	3.305E+00	3.414E+00	4.598E-01	1.385E+00	8.009E-02	1.045E+01	1.1	3.6	105.10	39523	1084.0	78310	4517	22

TABLE 12 (CONT'D)

ACCIDENT-FREE MODEL DATA USED FOR SENSITIVITY ANALYSIS

TIME SPANS 2 AND 6

Y(1)	Y(2)	Y(3)	Y(4)	Y(5)	Y(6)	Y(T)	F	TI	VSFPDT	PFOP	TFCNT	PD	SHOPED	NFLR
5.200E+00	9.185E+00	4.514E+00	6.628E-01	3.323E+00	6.305E-02	2.294E+01	.7	10.4	36.10	20477	400.0	26974	13265	22
1.800E+00	3.305E+00	3.414E+00	2.382E-01	1.155E+00	3.891E-02	9.955E+00	1.1	3.6	36.10	20477	400.0	26974	13265	22
5.200E+00	9.185E+00	4.514E+00	1.279E+00	3.323E+00	6.305E-02	2.354E+01	.7	10.4	36.10	39523	400.0	26974	13265	22
1.800E+00	3.305E+00	3.414E+00	4.598E-01	1.155E+00	3.891E-02	1.019E+01	1.1	3.6	36.10	39523	400.0	26974	13265	22
5.200E+00	9.185E+00	4.514E+00	6.628E-01	4.307E+00	6.305E-02	2.394E+01	.7	10.4	36.10	20477	1084.0	26974	13265	22
1.800E+00	3.305E+00	3.414E+00	2.382E-01	1.505E+00	3.891E-02	1.031E+01	1.1	3.6	36.10	20477	1084.0	26974	13265	22
5.200E+00	9.185E+00	4.514E+00	1.279E+00	4.307E+00	6.305E-02	2.454E+01	.7	10.4	36.10	39523	1084.0	26974	13265	22
1.800E+00	3.305E+00	3.414E+00	4.598E-01	1.505E+00	3.891E-02	1.053E+01	1.1	3.6	36.10	39523	1084.0	26974	13265	22
5.200E+00	9.185E+00	4.514E+00	6.628E-01	3.323E+00	1.435E-01	2.304E+01	.7	10.4	36.10	20477	400.0	78710	13265	22
1.800E+00	3.305E+00	3.414E+00	2.382E-01	1.155E+00	8.855E-02	1.001E+01	1.1	3.6	36.10	20477	400.0	78710	13265	22
5.200E+00	9.185E+00	4.514E+00	1.279E+00	3.323E+00	1.435E-01	2.364E+01	.7	10.4	36.10	39523	400.0	78710	13265	22
1.800E+00	3.305E+00	3.414E+00	4.598E-01	1.155E+00	8.855E-02	1.023E+01	1.1	3.6	36.10	39523	400.0	78710	13265	22
5.200E+00	9.185E+00	4.514E+00	6.628E-01	4.307E+00	1.435E-01	2.404E+01	.7	10.4	36.10	20477	1084.0	78710	13265	22
1.800E+00	3.305E+00	3.414E+00	2.382E-01	1.505E+00	8.855E-02	1.036E+01	1.1	3.6	36.10	20477	1084.0	78710	13265	22
5.200E+00	9.185E+00	4.514E+00	6.628E-01	3.017E+00	6.305E-02	2.264E+01	.7	10.4	105.10	20477	400.0	26974	13265	22
1.800E+00	3.305E+00	3.414E+00	2.382E-01	1.050E+00	3.891E-02	9.845E+00	1.1	3.6	105.10	20477	400.0	26974	13265	22
5.200E+00	9.185E+00	4.514E+00	1.279E+00	3.017E+00	6.305E-02	2.324E+01	.7	10.4	105.10	39523	400.0	26974	13265	22
1.800E+00	3.305E+00	3.414E+00	4.598E-01	1.050E+00	3.891E-02	1.007E+01	1.1	3.6	105.10	39523	400.0	26974	13265	22
5.200E+00	9.185E+00	4.514E+00	6.628E-01	3.962E+00	6.305E-02	2.354E+01	.7	10.4	105.10	20477	1084.0	26974	13265	22
1.800E+00	3.305E+00	3.414E+00	2.382E-01	1.385E+00	3.891E-02	1.019E+01	1.1	3.6	105.10	20477	1084.0	26974	13265	22
5.200E+00	9.185E+00	4.514E+00	1.279E+00	3.962E+00	6.305E-02	2.424E+01	.7	10.4	105.10	39523	1084.0	26974	13265	22
1.800E+00	3.305E+00	3.414E+00	4.598E-01	1.385E+00	3.891E-02	1.041E+01	1.1	3.6	105.10	39523	1084.0	26974	13265	22
5.200E+00	9.185E+00	4.514E+00	6.628E-01	3.017E+00	1.435E-01	2.274E+01	.7	10.4	105.10	20477	400.0	78710	13265	22
1.800E+00	3.305E+00	3.414E+00	2.382E-01	1.050E+00	8.855E-02	9.895E+00	1.1	3.6	105.10	20477	400.0	78710	13265	22
5.200E+00	9.185E+00	4.514E+00	1.279E+00	3.017E+00	1.435E-01	2.334E+01	.7	10.4	105.10	39523	400.0	78710	13265	22
1.800E+00	3.305E+00	3.414E+00	4.598E-01	1.050E+00	8.855E-02	1.012E+01	1.1	3.6	105.10	39523	400.0	78710	13265	22
5.200E+00	9.185E+00	4.514E+00	6.628E-01	3.962E+00	1.435E-01	2.364E+01	.7	10.4	105.10	20477	1084.0	78710	13265	22
1.800E+00	3.305E+00	3.414E+00	2.382E-01	1.385E+00	8.855E-02	1.024E+01	1.1	3.6	105.10	20477	1084.0	78710	13265	22
5.200E+00	9.185E+00	4.514E+00	1.279E+00	3.962E+00	1.435E-01	2.424E+01	.7	10.4	105.10	39523	1084.0	78710	13265	22
1.800E+00	3.305E+00	3.414E+00	4.598E-01	1.385E+00	8.855E-02	1.046E+01	1.1	3.6	105.10	39523	1084.0	78710	13265	22
3.500E+00	6.318E+00	4.514E+00	6.675E-01	2.278E+00	1.794E-01	1.744E+01	.9	7.0	70.60	30000	742.0	52642	8891	15
3.500E+00	6.318E+00	4.514E+00	6.675E-01	2.278E+00	2.573E-01	1.754E+01	.9	7.0	70.60	30000	742.0	104723	8891	15
0.	0.	0.	0.	0.	0.	0.	.9	0.0	70.60	30000	742.0	52642	8891	15
7.000E+00	1.264E+01	4.514E+00	1.335E+00	4.555E+00	2.787E-01	3.024E+01	.9	14.0	70.60	30000	742.0	52642	8891	15
3.500E+00	6.017E+00	4.514E+00	6.367E-01	2.255E+00	3.153E-02	1.695E+01	.5	7.0	70.60	30000	742.0	52642	8891	15
3.500E+00	6.511E+00	4.514E+00	6.875E-01	2.292E+00	1.994E-01	1.779E+01	1.3	7.0	70.60	30000	742.0	52642	8891	15
3.500E+00	6.318E+00	4.514E+00	6.675E-01	1.107E+01	1.394E-01	2.624E+01	.9	7.0	.60	30000	742.0	52642	8891	15
3.500E+00	6.318E+00	4.514E+00	6.675E-01	2.224E+00	1.394E-01	1.734E+01	.9	7.0	140.60	30000	742.0	52642	8891	15
3.500E+00	6.318E+00	4.514E+00	2.376E-01	2.278E+00	1.394E-01	1.694E+01	.9	7.0	70.60	10678	742.0	52642	8891	15
3.500E+00	6.318E+00	4.514E+00	1.397E+00	2.278E+00	1.394E-01	1.784E+01	.9	7.0	70.60	49322	742.0	52642	8891	15
3.500E+00	6.318E+00	4.514E+00	6.675E-01	2.630E-01	1.394E-01	1.544E+01	.9	7.0	70.60	30000	43.0	52642	8891	15
3.500E+00	6.318E+00	4.514E+00	6.675E-01	2.934E+00	1.394E-01	1.804E+01	.9	7.0	70.60	30000	1435.0	52642	8891	15
3.500E+00	6.318E+00	4.514E+00	6.675E-01	2.278E+00	2.141E-02	1.734E+01	.9	7.0	70.60	30000	742.0	561	8891	15
3.500E+00	6.318E+00	4.514E+00	6.675E-01	2.278E+00	1.193E-01	1.764E+01	.9	7.0	70.60	30000	742.0	52642	16	15
3.500E+00	6.318E+00	4.514E+00	6.675E-01	2.278E+00	1.595E-01	1.744E+01	.9	7.0	70.60	30000	742.0	52642	17766	15
3.500E+00	6.318E+00	4.514E+00	6.675E-01	2.278E+00	6.286E-01	1.794E+01	.9	7.0	70.60	30000	742.0	52642	8891	1
3.500E+00	6.318E+00	4.514E+00	6.675E-01	2.278E+00	7.262E-02	1.734E+01	.9	7.0	70.60	30000	742.0	52642	8891	29

TABLE 17 (CONT'D)

ACCIDENT-FREE MODEL DATA USED FOR SENSITIVITY ANALYSIS

TIME SPANS 3 AND 5

Y(1)	Y(2)	Y(3)	Y(4)	Y(5)	Y(6)	Y(7)	F	TI	WSHPOT	PCRP	ICONT	PP	SHOPPD	NFLP
5.200E+00	9.548E+00	3.420E+00	2.330E-01	1.213E+00	9.874E-02	1.967E+01	1.1	10.4	107.10	12991	322.0	4714	13265	8
1.800E+00	3.179E+00	2.571E+00	1.306E-01	4.170E-01	1.921E-02	8.119E+00	.7	3.6	107.10	25073	322.0	4714	13265	8
5.200E+00	9.548E+00	3.420E+00	3.917E-01	1.213E+00	9.874E-02	1.987E+01	1.1	10.4	107.10	25073	322.0	4714	13265	8
1.800E+00	3.179E+00	2.571E+00	6.765E-02	6.446E-01	1.921E-02	8.289E+00	.7	3.6	107.10	12991	478.0	4714	13265	8
5.200E+00	9.548E+00	3.420E+00	2.330E-01	1.886E+00	9.874E-02	2.037E+01	1.1	10.4	107.10	12991	478.0	4714	13265	8
1.800E+00	3.179E+00	2.571E+00	1.306E-01	6.446E-01	1.921E-02	8.349E+00	.7	3.6	107.10	25073	478.0	4714	13265	8
5.200E+00	9.548E+00	3.420E+00	3.917E-01	1.886E+00	9.874E-02	2.057E+01	1.1	10.4	107.10	25073	478.0	4714	13265	8
1.800E+00	3.179E+00	2.571E+00	6.765E-02	4.170E-01	2.707E-02	8.069E+00	.7	3.6	107.10	12991	322.0	11374	13265	8
5.200E+00	9.548E+00	3.420E+00	2.330E-01	1.213E+00	1.392E-01	1.977E+01	1.1	10.4	107.10	12991	322.0	11374	13265	8
1.800E+00	3.179E+00	2.571E+00	1.306E-01	4.170E-01	2.707E-02	8.129E+00	.7	3.6	107.10	25073	322.0	11374	13265	8
5.200E+00	9.548E+00	3.420E+00	3.917E-01	1.213E+00	1.392E-01	1.997E+01	1.1	10.4	107.10	25073	322.0	11374	13265	8
1.800E+00	3.179E+00	2.571E+00	6.765E-02	6.446E-01	2.707E-02	8.289E+00	.7	3.6	107.10	12991	478.0	11374	13265	8
5.200E+00	9.548E+00	3.420E+00	2.330E-01	1.886E+00	1.392E-01	2.037E+01	1.1	10.4	107.10	12991	478.0	11374	13265	8
1.800E+00	3.179E+00	2.571E+00	1.306E-01	6.446E-01	2.707E-02	8.359E+00	.7	3.6	107.10	25073	478.0	11374	13265	8
5.200E+00	9.548E+00	3.420E+00	3.917E-01	1.886E+00	1.392E-01	2.057E+01	1.1	10.4	107.10	25073	478.0	11374	13265	8
5.200E+00	9.185E+00	3.420E+00	1.954E-01	1.394E+00	1.037E-02	1.944E+01	.7	10.4	36.90	12991	322.0	4714	4517	22
1.800E+00	3.305E+00	2.587E+00	7.326E-02	4.857E-01	6.398E-03	8.255E+00	1.1	3.6	36.90	12991	322.0	4714	4517	22
5.200E+00	9.185E+00	3.420E+00	3.772E-01	1.394E+00	1.037E-02	1.964E+01	.7	10.4	36.90	25073	322.0	4714	4517	22
1.800E+00	3.305E+00	2.587E+00	1.356E-01	4.857E-01	6.398E-03	8.315E+00	1.1	3.6	36.90	25073	322.0	4714	4517	22
5.200E+00	9.185E+00	3.420E+00	1.954E-01	2.110E+00	1.037E-02	2.014E+01	.7	10.4	36.90	12991	478.0	4714	4517	22
1.800E+00	3.305E+00	2.587E+00	7.326E-02	7.386E-01	6.398E-03	8.505E+00	1.1	3.6	36.90	12991	478.0	4714	4517	22
5.200E+00	9.185E+00	3.420E+00	3.772E-01	2.110E+00	1.037E-02	2.034E+01	.7	10.4	36.90	25073	478.0	4714	4517	22
1.800E+00	3.305E+00	2.587E+00	1.356E-01	7.386E-01	6.398E-03	8.575E+00	1.1	3.6	36.90	25073	478.0	4714	4517	22
5.200E+00	9.185E+00	3.420E+00	1.954E-01	1.394E+00	1.887E-02	1.944E+01	.7	10.4	36.90	12991	322.0	11374	4517	22
1.800E+00	3.305E+00	2.587E+00	7.026E-02	4.857E-01	1.164E-02	8.255E+00	1.1	3.6	36.90	12991	322.0	11374	4517	22
5.200E+00	9.185E+00	3.420E+00	3.772E-01	1.394E+00	1.887E-02	1.964E+01	.7	10.4	36.90	25073	322.0	11374	4517	22
1.800E+00	3.305E+00	2.587E+00	1.356E-01	4.857E-01	1.164E-02	8.325E+00	1.1	3.6	36.90	25073	322.0	11374	4517	22
5.200E+00	9.185E+00	3.420E+00	1.954E-01	2.110E+00	1.887E-02	2.014E+01	.7	10.4	36.90	12991	478.0	11374	4517	22
1.800E+00	3.305E+00	2.587E+00	7.326E-02	7.386E-01	1.164E-02	8.515E+00	1.1	3.6	36.90	12991	478.0	11374	4517	22
5.200E+00	9.185E+00	3.420E+00	3.772E-01	2.110E+00	1.887E-02	2.034E+01	.7	10.4	36.90	25073	478.0	11374	4517	22
1.800E+00	3.305E+00	2.587E+00	1.356E-01	7.386E-01	1.164E-02	8.575E+00	1.1	3.6	36.90	25073	478.0	11374	4517	22
5.200E+00	9.185E+00	3.420E+00	1.954E-01	1.205E+00	1.037E-02	1.924E+01	.7	10.4	107.10	12991	322.0	4714	4517	22
1.800E+00	3.305E+00	2.587E+00	7.326E-02	4.200E-01	6.398E-03	8.185E+00	1.1	3.6	107.10	12991	322.0	4714	4517	22
5.200E+00	9.185E+00	3.420E+00	3.772E-01	1.205E+00	1.037E-02	1.944E+01	.7	10.4	107.10	25073	322.0	4714	4517	22
1.800E+00	3.305E+00	2.587E+00	1.356E-01	4.200E-01	6.398E-03	8.255E+00	1.1	3.6	107.10	25073	322.0	4714	4517	22
5.200E+00	9.185E+00	3.420E+00	1.954E-01	1.862E+00	1.037E-02	1.984E+01	.7	10.4	107.10	12991	478.0	4714	4517	22
1.800E+00	3.305E+00	2.587E+00	7.326E-02	6.529E-01	6.398E-03	8.425E+00	1.1	3.6	107.10	12991	478.0	4714	4517	22
5.200E+00	9.185E+00	3.420E+00	3.772E-01	1.862E+00	1.037E-02	2.004E+01	.7	10.4	107.10	25073	478.0	4714	4517	22
1.800E+00	3.305E+00	2.587E+00	1.356E-01	6.529E-01	6.398E-03	8.495E+00	1.1	3.6	107.10	25073	478.0	4714	4517	22
5.200E+00	9.185E+00	3.420E+00	1.954E-01	1.205E+00	1.887E-02	1.924E+01	.7	10.4	107.10	12991	322.0	11374	4517	22
1.800E+00	3.305E+00	2.587E+00	7.326E-02	4.200E-01	1.164E-02	8.195E+00	1.1	3.6	107.10	12991	322.0	11374	4517	22
5.200E+00	9.185E+00	3.420E+00	3.772E-01	1.205E+00	1.887E-02	1.944E+01	.7	10.4	107.10	25073	322.0	11374	4517	22
1.800E+00	3.305E+00	2.587E+00	1.356E-01	4.200E-01	1.164E-02	8.255E+00	1.1	3.6	107.10	25073	322.0	11374	4517	22
5.200E+00	9.185E+00	3.420E+00	1.954E-01	1.862E+00	1.887E-02	1.984E+01	.7	10.4	107.10	12991	478.0	11374	4517	22
1.800E+00	3.305E+00	2.587E+00	7.326E-02	6.529E-01	1.164E-02	8.425E+00	1.1	3.6	107.10	12991	478.0	11374	4517	22
5.200E+00	9.185E+00	3.420E+00	3.772E-01	1.862E+00	1.887E-02	2.004E+01	.7	10.4	107.10	25073	478.0	11374	4517	22
1.800E+00	3.305E+00	2.587E+00	1.356E-01	6.529E-01	1.164E-02	8.495E+00	1.1	3.6	107.10	25073	478.0	11374	4517	22
5.200E+00	9.185E+00	3.420E+00	1.954E-01	1.394E+00	2.075E-02	1.944E+01	.7	10.4	36.90	12991	322.0	4714	13265	22
1.800E+00	3.305E+00	2.587E+00	7.326E-02	4.857E-01	1.281E-02	8.255E+00	1.1	3.6	36.90	12991	322.0	4714	13265	22

TABLE 13 (CONTD)

ACCIDENT-FREE MODEL DATA USED FOR SENSITIVITY ANALYSIS

TIME SPANS 3 AND 5

Y(1)	Y(2)	Y(3)	Y(4)	Y(5)	Y(6)	Y(T)	E	TI	VSEPDT	PEOP	TECHT	PD	SHOPED	NELR
5.200E+00	9.185E+00	3.420E+00	3.772E-01	1.394E+00	2.075E-02	1.964E+01	.7	10.4	36.90	25073	322.0	4214	13265	22
1.800E+00	3.305E+00	2.587E+00	1.356E-01	4.857E-01	1.281E-02	8.325E+00	1.1	3.6	36.90	25073	322.0	4214	13265	22
5.200E+00	9.185E+00	3.420E+00	1.954E-01	2.110E+00	2.075E-02	2.014E+01	.7	10.4	36.90	12991	878.0	4214	13265	22
1.800E+00	3.305E+00	2.587E+00	7.026E-02	7.386E-01	1.281E-02	8.515E+00	1.1	3.6	36.90	12991	878.0	4214	13265	22
5.200E+00	9.185E+00	3.420E+00	3.772E-01	2.110E+00	2.075E-02	2.034E+01	.7	10.4	36.90	25073	878.0	4214	13265	22
1.800E+00	3.305E+00	2.587E+00	1.356E-01	7.386E-01	1.281E-02	8.575E+00	1.1	3.6	36.90	25073	878.0	4214	13265	22
5.200E+00	9.185E+00	3.420E+00	1.954E-01	1.394E+00	2.926E-02	1.944E+01	.7	10.4	36.90	12991	322.0	11374	13265	22
1.800E+00	3.305E+00	2.587E+00	7.026E-02	4.857E-01	1.805E-02	8.265E+00	1.1	3.6	36.90	12991	322.0	11374	13265	22
5.200E+00	9.185E+00	3.420E+00	3.772E-01	1.394E+00	2.926E-02	1.964E+01	.7	10.4	36.90	25073	322.0	11374	13265	22
1.800E+00	3.305E+00	2.587E+00	1.356E-01	4.857E-01	1.805E-02	8.335E+00	1.1	3.6	36.90	25073	322.0	11374	13265	22
5.200E+00	9.185E+00	3.420E+00	1.954E-01	2.110E+00	2.926E-02	2.014E+01	.7	10.4	36.90	12991	878.0	11374	13265	22
1.800E+00	3.305E+00	2.587E+00	7.026E-02	7.386E-01	1.805E-02	8.515E+00	1.1	3.6	36.90	12991	878.0	11374	13265	22
5.200E+00	9.185E+00	3.420E+00	3.772E-01	2.110E+00	2.926E-02	2.034E+01	.7	10.4	36.90	25073	878.0	11374	13265	22
1.800E+00	3.305E+00	2.587E+00	1.356E-01	7.386E-01	1.805E-02	8.585E+00	1.1	3.6	36.90	25073	878.0	11374	13265	22
5.200E+00	9.185E+00	3.420E+00	1.954E-01	1.205E+00	2.075E-02	1.924E+01	.7	10.4	107.10	12991	322.0	4214	13265	22
1.800E+00	3.305E+00	2.587E+00	7.026E-02	4.200E-01	1.281E-02	8.195E+00	1.1	3.6	107.10	12991	322.0	4214	13265	22
5.200E+00	9.185E+00	3.420E+00	3.772E-01	1.205E+00	2.075E-02	1.944E+01	.7	10.4	107.10	25073	322.0	4214	13265	22
1.800E+00	3.305E+00	2.587E+00	1.356E-01	4.200E-01	1.281E-02	8.265E+00	1.1	3.6	107.10	25073	322.0	4214	13265	22
5.200E+00	9.185E+00	3.420E+00	1.954E-01	1.862E+00	2.075E-02	1.984E+01	.7	10.4	107.10	12991	878.0	4214	13265	22
1.800E+00	3.305E+00	2.587E+00	7.026E-02	6.529E-01	1.281E-02	8.425E+00	1.1	3.6	107.10	12991	878.0	4214	13265	22
5.200E+00	9.185E+00	3.420E+00	3.772E-01	1.862E+00	2.075E-02	2.004E+01	.7	10.4	107.10	25073	878.0	4214	13265	22
1.800E+00	3.305E+00	2.587E+00	1.356E-01	6.529E-01	1.281E-02	8.495E+00	1.1	3.6	107.10	25073	878.0	4214	13265	22
5.200E+00	9.185E+00	3.420E+00	1.954E-01	1.205E+00	2.926E-02	1.924E+01	.7	10.4	107.10	12991	322.0	11374	13265	22
1.800E+00	3.305E+00	2.587E+00	7.026E-02	4.200E-01	1.805E-02	8.205E+00	1.1	3.6	107.10	12991	322.0	11374	13265	22
5.200E+00	9.185E+00	3.420E+00	3.772E-01	1.205E+00	2.926E-02	1.944E+01	.7	10.4	107.10	25073	322.0	11374	13265	22
1.800E+00	3.305E+00	2.587E+00	1.356E-01	4.200E-01	1.805E-02	8.265E+00	1.1	3.6	107.10	25073	322.0	11374	13265	22
5.200E+00	9.185E+00	3.420E+00	1.954E-01	1.862E+00	2.926E-02	1.994E+01	.7	10.4	107.10	12991	878.0	11374	13265	22
1.800E+00	3.305E+00	2.587E+00	7.026E-02	6.529E-01	1.805E-02	8.435E+00	1.1	3.6	107.10	12991	878.0	11374	13265	22
5.200E+00	9.185E+00	3.420E+00	3.772E-01	1.862E+00	2.926E-02	2.004E+01	.7	10.4	107.10	25073	878.0	11374	13265	22
1.800E+00	3.305E+00	2.587E+00	1.356E-01	6.529E-01	1.805E-02	8.495E+00	1.1	3.6	107.10	25073	878.0	11374	13265	22
3.500E+00	6.318E+00	3.420E+00	1.968E-01	1.172E+00	2.864E-02	1.464E+01	.9	7.0	72.00	19032	600.0	7794	8891	15
0.	0.	0.	0.	0.	0.	0.	.9	0.0	72.00	19032	600.0	7794	8891	15
7.000E+00	1.264E+01	3.420E+00	3.937E-01	2.344E+00	5.727E-02	2.584E+01	.9	14.0	72.00	19032	600.0	7794	8891	15
3.500E+00	6.017E+00	3.420E+00	1.577E-01	1.159E+00	6.480E-03	1.430E+01	.5	7.0	72.00	19032	600.0	7794	8891	15
3.500E+00	6.511E+00	3.420E+00	2.027E-01	1.181E+00	4.098E-02	1.490E+01	1.3	7.0	72.00	19032	600.0	7794	8891	15
3.500E+00	6.318E+00	3.420E+00	1.968E-01	8.365E+00	2.864E-02	2.184E+01	.9	7.0	.70	19032	600.0	7794	8891	15
3.500E+00	6.318E+00	3.420E+00	1.968E-01	1.129E+00	2.864E-02	1.464E+01	.9	7.0	143.30	19032	600.0	7794	8891	15
3.500E+00	6.318E+00	3.420E+00	7.006E-02	1.172E+00	2.864E-02	1.454E+01	.9	7.0	72.00	6774	600.0	7794	8891	15
3.500E+00	6.318E+00	3.420E+00	3.236E-01	1.172E+00	2.864E-02	1.474E+01	.9	7.0	72.00	31290	600.0	7794	8891	15
3.500E+00	6.318E+00	3.420E+00	1.968E-01	1.319E-01	2.864E-02	1.364E+01	.9	7.0	72.00	19032	36.0	7794	8891	15
3.500E+00	6.318E+00	3.420E+00	1.968E-01	1.539E+00	2.864E-02	1.504E+01	.9	7.0	72.00	19032	1164.0	7794	8891	15
3.500E+00	6.318E+00	3.420E+00	1.968E-01	1.172E+00	1.617E-02	1.464E+01	.9	7.0	72.00	19032	600.0	530	8891	15
3.500E+00	6.318E+00	3.420E+00	1.968E-01	1.172E+00	4.110E-02	1.464E+01	.9	7.0	72.00	19032	600.0	15058	8891	15
3.500E+00	6.318E+00	3.420E+00	1.968E-01	1.172E+00	1.340E-02	1.464E+01	.9	7.0	72.00	19032	600.0	7794	16	15
3.500E+00	6.318E+00	3.420E+00	1.968E-01	1.172E+00	4.787E-02	1.464E+01	.9	7.0	72.00	19032	600.0	7794	17766	15
3.500E+00	6.318E+00	3.420E+00	1.968E-01	1.172E+00	1.292E-01	1.474E+01	.9	7.0	72.00	19032	600.0	7794	8891	1
3.500E+00	6.318E+00	3.420E+00	1.968E-01	1.172E+00	1.492E-02	1.464E+01	.9	7.0	72.00	19032	600.0	7794	8891	29

TABLE 13

ACCIDENT-FREE MODEL DATA USED FOR SENSITIVITY ANALYSIS

TIME SPANS 3 AND 5

Y(1)	Y(2)	Y(3)	Y(4)	Y(5)	Y(6)	Y(7)	E	TI	VSEPDT	PEDD	TFCNT	PD	SHOPED	NFLR
1.800E+00	3.179E+00	2.571E+00	6.765E-02	4.826E-01	9.593E-03	8.139E+00	.7	3.6	36.90	12991	322.0	4214	4517	8
5.200E+00	9.548E+00	3.420E+00	2.030E-01	1.403E+00	4.932E-02	1.987E+01	1.1	10.4	36.90	12991	322.0	4214	4517	8
1.800E+00	3.179E+00	2.571E+00	1.306E-01	4.826E-01	9.593E-03	8.179E+00	.7	3.6	36.90	25073	322.0	4214	4517	8
5.200E+00	9.548E+00	3.420E+00	3.917E-01	1.403E+00	4.932E-02	1.997E+01	1.1	10.4	36.90	25073	322.0	4214	4517	8
1.800E+00	3.179E+00	2.571E+00	6.765E-02	7.303E-01	9.593E-03	8.359E+00	.7	3.6	36.90	12991	878.0	4214	4517	8
5.200E+00	9.548E+00	3.420E+00	2.030E-01	2.134E+00	4.932E-02	2.057E+01	1.1	10.4	36.90	12991	878.0	4214	4517	8
1.800E+00	3.179E+00	2.571E+00	1.306E-01	7.303E-01	9.593E-03	8.429E+00	.7	3.6	36.90	25073	878.0	4214	4517	8
5.200E+00	9.548E+00	3.420E+00	3.917E-01	2.134E+00	4.932E-02	2.077E+01	1.1	10.4	36.90	25073	878.0	4214	4517	8
1.800E+00	3.179E+00	2.571E+00	6.765E-02	4.826E-01	1.746E-02	8.119E+00	.7	3.6	36.90	12991	322.0	11374	4517	8
5.200E+00	9.548E+00	3.420E+00	2.030E-01	1.403E+00	8.977E-02	1.987E+01	1.1	10.4	36.90	12991	322.0	11374	4517	8
1.800E+00	3.179E+00	2.571E+00	1.306E-01	4.826E-01	1.746E-02	8.189E+00	.7	3.6	36.90	25073	322.0	11374	4517	8
5.200E+00	9.548E+00	3.420E+00	3.917E-01	1.403E+00	8.977E-02	2.007E+01	1.1	10.4	36.90	25073	322.0	11374	4517	8
1.800E+00	3.179E+00	2.571E+00	6.765E-02	7.303E-01	1.746E-02	8.369E+00	.7	3.6	36.90	12991	878.0	11374	4517	8
5.200E+00	9.548E+00	3.420E+00	2.030E-01	2.134E+00	8.977E-02	2.057E+01	1.1	10.4	36.90	12991	878.0	11374	4517	8
1.800E+00	3.179E+00	2.571E+00	1.306E-01	7.303E-01	1.746E-02	8.429E+00	.7	3.6	36.90	25073	878.0	11374	4517	8
5.200E+00	9.548E+00	3.420E+00	3.917E-01	2.134E+00	8.977E-02	2.077E+01	1.1	10.4	36.90	25073	878.0	11374	4517	8
1.800E+00	3.179E+00	2.571E+00	6.765E-02	4.170E-01	9.593E-03	8.049E+00	.7	3.6	107.10	12991	322.0	4214	4517	8
5.200E+00	9.548E+00	3.420E+00	2.030E-01	1.213E+00	4.932E-02	1.967E+01	1.1	10.4	107.10	12991	322.0	4214	4517	8
1.800E+00	3.179E+00	2.571E+00	1.306E-01	4.170E-01	9.593E-03	8.109E+00	.7	3.6	107.10	25073	322.0	4214	4517	8
5.200E+00	9.548E+00	3.420E+00	3.917E-01	1.213E+00	4.932E-02	1.987E+01	1.1	10.4	107.10	25073	322.0	4214	4517	8
1.800E+00	3.179E+00	2.571E+00	6.765E-02	6.446E-01	9.593E-03	8.279E+00	.7	3.6	107.10	12991	878.0	4214	4517	8
5.200E+00	9.548E+00	3.420E+00	2.030E-01	1.886E+00	4.932E-02	2.027E+01	1.1	10.4	107.10	12991	878.0	4214	4517	8
1.800E+00	3.179E+00	2.571E+00	1.306E-01	6.446E-01	9.593E-03	8.339E+00	.7	3.6	107.10	25073	878.0	4214	4517	8
5.200E+00	9.548E+00	3.420E+00	3.917E-01	1.886E+00	4.932E-02	2.047E+01	1.1	10.4	107.10	25073	878.0	4214	4517	8
1.800E+00	3.179E+00	2.571E+00	6.765E-02	4.170E-01	1.746E-02	8.059E+00	.7	3.6	107.10	12991	322.0	11374	4517	8
5.200E+00	9.548E+00	3.420E+00	2.030E-01	1.213E+00	8.977E-02	1.967E+01	1.1	10.4	107.10	12991	322.0	11374	4517	8
1.800E+00	3.179E+00	2.571E+00	1.306E-01	4.170E-01	1.746E-02	8.119E+00	.7	3.6	107.10	25073	322.0	11374	4517	8
5.200E+00	9.548E+00	3.420E+00	3.917E-01	1.213E+00	8.977E-02	1.987E+01	1.1	10.4	107.10	25073	322.0	11374	4517	8
1.800E+00	3.179E+00	2.571E+00	6.765E-02	6.446E-01	1.746E-02	8.279E+00	.7	3.6	107.10	12991	878.0	11374	4517	8
5.200E+00	9.548E+00	3.420E+00	2.030E-01	1.886E+00	8.977E-02	2.037E+01	1.1	10.4	107.10	12991	878.0	11374	4517	8
1.800E+00	3.179E+00	2.571E+00	1.306E-01	6.446E-01	1.746E-02	8.349E+00	.7	3.6	107.10	25073	878.0	11374	4517	8
5.200E+00	9.548E+00	3.420E+00	3.917E-01	1.886E+00	8.977E-02	2.057E+01	1.1	10.4	107.10	25073	878.0	11374	4517	8
1.800E+00	3.179E+00	2.571E+00	6.765E-02	4.826E-01	1.921E-02	8.119E+00	.7	3.6	36.90	12991	322.0	4214	13265	8
5.200E+00	9.548E+00	3.420E+00	2.030E-01	1.403E+00	9.874E-02	1.987E+01	1.1	10.4	36.90	12991	322.0	4214	13265	8
1.800E+00	3.179E+00	2.571E+00	1.306E-01	4.826E-01	1.921E-02	8.189E+00	.7	3.6	36.90	25073	322.0	4214	13265	8
5.200E+00	9.548E+00	3.420E+00	3.917E-01	1.403E+00	9.874E-02	2.007E+01	1.1	10.4	36.90	25073	322.0	4214	13265	8
1.800E+00	3.179E+00	2.571E+00	6.765E-02	7.303E-01	1.921E-02	8.359E+00	.7	3.6	36.90	12991	878.0	4214	13265	8
5.200E+00	9.548E+00	3.420E+00	2.030E-01	2.134E+00	9.874E-02	2.057E+01	1.1	10.4	36.90	12991	878.0	4214	13265	8
1.800E+00	3.179E+00	2.571E+00	1.306E-01	7.303E-01	1.921E-02	8.429E+00	.7	3.6	36.90	25073	878.0	4214	13265	8
5.200E+00	9.548E+00	3.420E+00	3.917E-01	2.134E+00	9.874E-02	2.077E+01	1.1	10.4	36.90	25073	878.0	4214	13265	8
1.800E+00	3.179E+00	2.571E+00	6.765E-02	4.826E-01	2.707E-02	8.129E+00	.7	3.6	36.90	12991	322.0	11374	13265	8
5.200E+00	9.548E+00	3.420E+00	2.030E-01	1.403E+00	1.392E-01	1.987E+01	1.1	10.4	36.90	12991	322.0	11374	13265	8
1.800E+00	3.179E+00	2.571E+00	1.306E-01	4.826E-01	2.707E-02	8.199E+00	.7	3.6	36.90	25073	322.0	11374	13265	8
5.200E+00	9.548E+00	3.420E+00	3.917E-01	1.403E+00	1.392E-01	2.007E+01	1.1	10.4	36.90	25073	322.0	11374	13265	8
1.800E+00	3.179E+00	2.571E+00	6.765E-02	7.303E-01	2.707E-02	8.379E+00	.7	3.6	36.90	12991	878.0	11374	13265	8
5.200E+00	9.548E+00	3.420E+00	2.030E-01	2.134E+00	1.392E-01	2.067E+01	1.1	10.4	36.90	12991	878.0	11374	13265	8
1.800E+00	3.179E+00	2.571E+00	1.306E-01	7.303E-01	2.707E-02	8.439E+00	.7	3.6	36.90	25073	878.0	11374	13265	8
5.200E+00	9.548E+00	3.420E+00	3.917E-01	2.134E+00	1.392E-01	2.087E+01	1.1	10.4	36.90	25073	878.0	11374	13265	8
1.800E+00	3.179E+00	2.571E+00	6.765E-02	4.170E-01	1.921E-02	8.059E+00	.7	3.6	107.10	12991	322.0	4214	13265	8

TABLE 14

ACCIDENT-FREE MODEL DATA USED FOR SENSITIVITY ANALYSIS

TIME SPAN 4

Y(1)	Y(2)	Y(3)	Y(4)	Y(5)	Y(6)	Y(T)	E	TI	VSEPOT	PEDD	TECNT	PD	SHOPED	NELR
1.800E+00	3.179E+00	2.977E+00	2.856E-01	4.122E-01	1.111E-02	8.669E+00	.7	3.6	39.30	48326	216.0	4214	4517	8
5.200E+00	9.548E+00	3.961E+00	8.568E-01	1.197E+00	5.712E-02	2.087E+01	1.1	10.4	39.30	48326	216.0	4214	4517	8
1.800E+00	3.179E+00	2.977E+00	5.512E-01	4.122E-01	1.111E-02	8.939E+00	.7	3.6	39.30	93274	216.0	4214	4517	8
5.200E+00	9.548E+00	3.961E+00	1.654E+00	1.197E+00	5.712E-02	2.157E+01	1.1	10.4	39.30	93274	216.0	4214	4517	8
1.800E+00	3.179E+00	2.977E+00	2.856E-01	8.462E-01	1.111E-02	9.899E+00	.7	3.6	39.30	48326	588.0	4214	4517	8
5.200E+00	9.548E+00	3.961E+00	8.568E-01	2.462E+00	5.712E-02	2.207E+01	1.1	10.4	39.30	48326	588.0	4214	4517	8
1.800E+00	3.179E+00	2.977E+00	5.512E-01	8.462E-01	1.111E-02	9.369E+00	.7	3.6	39.30	93274	588.0	4214	4517	8
5.200E+00	9.548E+00	3.961E+00	1.654E+00	2.462E+00	5.712E-02	2.287E+01	1.1	10.4	39.30	93274	588.0	4214	4517	8
1.800E+00	3.179E+00	2.977E+00	2.856E-01	4.122E-01	2.022E-02	8.679E+00	.7	3.6	39.30	48326	216.0	11374	4517	8
5.200E+00	9.548E+00	3.961E+00	8.568E-01	1.197E+00	1.040E-01	2.087E+01	1.1	10.4	39.30	48326	216.0	11374	4517	8
1.800E+00	3.179E+00	2.977E+00	5.512E-01	4.122E-01	2.022E-02	8.939E+00	.7	3.6	39.30	93274	216.0	11374	4517	8
5.200E+00	9.548E+00	3.961E+00	1.654E+00	.197E+00	1.040E-01	2.167E+01	1.1	10.4	39.30	93274	216.0	11374	4517	8
1.800E+00	3.179E+00	2.977E+00	2.856E-01	.462E-01	2.022E-02	9.109E+00	.7	3.6	39.30	48326	588.0	11374	4517	8
5.200E+00	9.548E+00	3.961E+00	8.568E-01	2.462E+00	1.040E-01	2.217E+01	1.1	10.4	39.30	48326	588.0	11374	4517	8
1.800E+00	3.179E+00	2.977E+00	5.512E-01	8.462E-01	2.022E-02	9.379E+00	.7	3.6	39.30	93274	588.0	11374	4517	8
5.200E+00	9.548E+00	3.961E+00	1.654E+00	2.462E+00	1.040E-01	2.297E+01	1.1	10.4	39.30	93274	588.0	11374	4517	8
1.800E+00	3.179E+00	2.977E+00	2.856E-01	3.726E-01	1.111E-02	8.629E+00	.7	3.6	114.40	48326	216.0	4214	4517	8
5.200E+00	9.548E+00	3.961E+00	8.568E-01	1.083E+00	5.712E-02	2.067E+01	1.1	10.4	114.40	48326	216.0	4214	4517	8
1.800E+00	3.179E+00	2.977E+00	5.512E-01	3.726E-01	1.111E-02	8.899E+00	.7	3.6	114.40	93274	216.0	4214	4517	8
5.200E+00	9.548E+00	3.961E+00	1.654E+00	1.083E+00	5.712E-02	2.147E+01	1.1	10.4	114.40	93274	216.0	4214	4517	8
1.800E+00	3.179E+00	2.977E+00	2.856E-01	7.686E-01	1.111E-02	9.029E+00	.7	3.6	114.40	48326	588.0	4214	4517	8
5.200E+00	9.548E+00	3.961E+00	8.568E-01	2.238E+00	5.712E-02	2.187E+01	1.1	10.4	114.40	48326	588.0	4214	4517	8
1.800E+00	3.179E+00	2.977E+00	5.512E-01	7.686E-01	1.111E-02	9.289E+00	.7	3.6	114.40	93274	588.0	4214	4517	8
5.200E+00	9.548E+00	3.961E+00	1.654E+00	2.238E+00	5.712E-02	2.267E+01	1.1	10.4	114.40	93274	588.0	4214	4517	8
1.800E+00	3.179E+00	2.977E+00	2.856E-01	3.726E-01	2.022E-02	8.639E+00	.7	3.6	114.40	48326	216.0	11374	4517	8
5.200E+00	9.548E+00	3.961E+00	8.568E-01	1.083E+00	1.040E-01	2.077E+01	1.1	10.4	114.40	48326	216.0	11374	4517	8
1.800E+00	3.179E+00	2.977E+00	5.512E-01	3.726E-01	2.022E-02	8.909E+00	.7	3.6	114.40	93274	216.0	11374	4517	8
5.200E+00	9.548E+00	3.961E+00	1.654E+00	1.083E+00	1.040E-01	2.157E+01	1.1	10.4	114.40	93274	216.0	11374	4517	8
1.800E+00	3.179E+00	2.977E+00	2.856E-01	7.686E-01	2.022E-02	9.039E+00	.7	3.6	114.40	48326	588.0	11374	4517	8
5.200E+00	9.548E+00	3.961E+00	8.568E-01	2.238E+00	1.040E-01	2.197E+01	1.1	10.4	114.40	48326	588.0	11374	4517	8
1.800E+00	3.179E+00	2.977E+00	5.512E-01	7.686E-01	2.022E-02	9.299E+00	.7	3.6	114.40	93274	588.0	11374	4517	8
5.200E+00	9.548E+00	3.961E+00	1.654E+00	2.238E+00	1.040E-01	2.267E+01	1.1	10.4	114.40	93274	588.0	11374	4517	8
1.800E+00	3.179E+00	2.977E+00	2.856E-01	4.122E-01	2.224E-02	8.679E+00	.7	3.6	39.30	48326	216.0	4214	13265	8
5.200E+00	9.548E+00	3.961E+00	8.568E-01	1.197E+00	1.144E-01	2.097E+01	1.1	10.4	39.30	48326	216.0	4214	13265	8
1.800E+00	3.179E+00	2.977E+00	5.512E-01	4.122E-01	2.224E-02	8.949E+00	.7	3.6	39.30	93274	216.0	4214	13265	8
5.200E+00	9.548E+00	3.961E+00	1.654E+00	1.197E+00	1.144E-01	2.167E+01	1.1	10.4	39.30	93274	216.0	4214	13265	8
1.800E+00	3.179E+00	2.977E+00	2.856E-01	8.462E-01	2.224E-02	9.119E+00	.7	3.6	39.30	48326	588.0	4214	13265	8
5.200E+00	9.548E+00	3.961E+00	8.568E-01	2.462E+00	1.144E-01	2.217E+01	1.1	10.4	39.30	48326	588.0	4214	13265	8
1.800E+00	3.179E+00	2.977E+00	5.512E-01	8.462E-01	2.224E-02	9.379E+00	.7	3.6	39.30	93274	588.0	4214	13265	8
5.200E+00	9.548E+00	3.961E+00	1.654E+00	2.462E+00	1.144E-01	2.297E+01	1.1	10.4	39.30	93274	588.0	4214	13265	8
1.800E+00	3.179E+00	2.977E+00	2.856E-01	4.122E-01	3.135E-02	8.689E+00	.7	3.6	39.30	48326	216.0	11374	13265	8
5.200E+00	9.548E+00	3.961E+00	8.568E-01	1.197E+00	1.612E-01	2.097E+01	1.1	10.4	39.30	48326	216.0	11374	13265	8
1.800E+00	3.179E+00	2.977E+00	5.512E-01	4.122E-01	3.135E-02	8.959E+00	.7	3.6	39.30	93274	216.0	11374	13265	8
5.200E+00	9.548E+00	3.961E+00	1.654E+00	1.197E+00	1.612E-01	2.177E+01	1.1	10.4	39.30	93274	216.0	11374	13265	8
1.800E+00	3.179E+00	2.977E+00	2.856E-01	8.462E-01	3.135E-02	9.119E+00	.7	3.6	39.30	48326	588.0	11374	13265	8
5.200E+00	9.548E+00	3.961E+00	8.568E-01	2.462E+00	1.612E-01	2.217E+01	1.1	10.4	39.30	48326	588.0	11374	13265	8
1.800E+00	3.179E+00	2.977E+00	5.512E-01	8.462E-01	3.135E-02	9.389E+00	.7	3.6	39.30	93274	588.0	11374	13265	8
5.200E+00	9.548E+00	3.961E+00	1.654E+00	2.462E+00	1.612E-01	2.297E+01	1.1	10.4	39.30	93274	588.0	11374	13265	8
1.800E+00	3.179E+00	2.977E+00	2.856E-01	3.726E-01	2.224E-02	8.639E+00	.7	3.6	114.40	48326	216.0	4214	13265	8

TABLE 14 (CONTD)

ACCIDENT-FREE MODEL DATA USED FOR SENSITIVITY ANALYSIS

TIME SPAN 4

Y(1)	Y(2)	Y(3)	Y(4)	Y(5)	Y(6)	Y(7)	E	TI	WSEPDT	PEOP	TECNT	PO	SHCPED	NELR
5.200E+00	9.548E+00	3.961E+00	8.568E-01	1.083E+00	1.144E-01	2.077E+01	1.1	10.4	114.40	48326	216.0	4214	13265	8
1.800E+00	3.179E+00	2.977E+00	5.512E-01	3.726E-01	2.224E-02	8.909E+00	.7	3.6	114.40	93274	216.0	4214	13265	8
5.200E+00	9.548E+00	3.961E+00	1.654E+00	1.083E+00	1.144E-01	2.157E+01	1.1	10.4	114.40	93274	216.0	4214	13265	8
1.800E+00	3.179E+00	2.977E+00	2.856E-01	7.686E-01	2.224E-02	9.039E+00	.7	3.6	114.40	48326	588.0	4214	13265	8
5.200E+00	9.548E+00	3.961E+00	8.568E-01	2.238E+00	1.144E-01	2.187E+01	1.1	10.4	114.40	48326	588.0	4214	13265	8
1.800E+00	3.179E+00	2.977E+00	5.512E-01	7.686E-01	2.224E-02	9.299E+00	.7	3.6	114.40	93274	588.0	4214	13265	8
5.200E+00	9.548E+00	3.961E+00	1.654E+00	2.238E+00	1.144E-01	2.267E+01	1.1	10.4	114.40	93274	588.0	4214	13265	8
1.800E+00	3.179E+00	2.977E+00	2.856E-01	3.726E-01	3.135E-02	8.649E+00	.7	3.6	114.40	48326	216.0	11374	13265	8
5.200E+00	9.548E+00	3.961E+00	8.568E-01	1.083E+00	1.612E-01	2.077E+01	1.1	10.4	114.40	48326	216.0	11374	13265	8
1.800E+00	3.179E+00	2.977E+00	5.512E-01	3.726E-01	3.135E-02	8.919E+00	.7	3.6	114.40	93274	216.0	11374	13265	8
5.200E+00	9.548E+00	3.961E+00	1.654E+00	1.083E+00	1.612E-01	2.157E+01	1.1	10.4	114.40	93274	216.0	11374	13265	8
1.800E+00	3.179E+00	2.977E+00	2.856E-01	7.686E-01	3.135E-02	9.049E+00	.7	3.6	114.40	48326	588.0	11374	13265	8
5.200E+00	9.548E+00	3.961E+00	8.568E-01	2.238E+00	1.612E-01	2.197E+01	1.1	10.4	114.40	48326	588.0	11374	13265	8
1.800E+00	3.179E+00	2.977E+00	5.512E-01	7.686E-01	3.135E-02	9.303E+00	.7	3.6	114.40	93274	588.0	11374	13265	8
5.200E+00	9.548E+00	3.961E+00	1.654E+00	2.238E+00	1.612E-01	2.277E+01	1.1	10.4	114.40	93274	588.0	11374	13265	8
5.200E+00	9.185E+00	3.961E+00	8.250E-01	1.191E+00	1.201E-02	2.034E+01	.7	10.4	39.30	48326	216.0	4214	4517	22
1.800E+00	3.305E+00	2.996E+00	2.366E-01	4.144E-01	7.409E-03	8.515E+00	1.1	3.6	39.30	48326	216.0	4214	4517	22
5.200E+00	9.185E+00	3.961E+00	1.592E+00	1.191E+00	1.201E-02	2.114E+01	.7	10.4	39.30	93274	216.0	4214	4517	22
1.800E+00	3.305E+00	2.996E+00	5.724E-01	4.144E-01	7.409E-03	9.395E+00	1.1	3.6	39.30	93274	216.0	4214	4517	22
5.200E+00	9.185E+00	3.961E+00	8.250E-01	2.445E+00	1.201E-02	2.164E+01	.7	10.4	39.30	48326	588.0	4214	4517	22
1.800E+00	3.305E+00	2.996E+00	2.966E-01	8.522E-01	7.409E-03	9.255E+00	1.1	3.6	39.30	48326	588.0	4214	4517	22
5.200E+00	9.185E+00	3.961E+00	1.592E+00	2.445E+00	1.201E-02	2.244E+01	.7	10.4	39.30	93274	588.0	4214	4517	22
1.800E+00	3.305E+00	2.996E+00	5.724E-01	8.522E-01	7.409E-03	9.535E+00	1.1	3.6	39.30	93274	588.0	4214	4517	22
5.200E+00	9.185E+00	3.961E+00	8.250E-01	1.191E+00	2.185E-02	2.034E+01	.7	10.4	39.30	48326	216.0	11374	4517	22
1.800E+00	3.305E+00	2.996E+00	2.366E-01	4.144E-01	1.349E-02	8.825E+00	1.1	3.6	39.30	48326	216.0	11374	4517	22
5.200E+00	9.185E+00	3.961E+00	1.592E+00	1.191E+00	2.185E-02	2.114E+01	.7	10.4	39.30	93274	216.0	11374	4517	22
1.800E+00	3.305E+00	2.996E+00	5.724E-01	4.144E-01	1.349E-02	9.105E+00	1.1	3.6	39.30	93274	216.0	11374	4517	22
5.200E+00	9.185E+00	3.961E+00	8.250E-01	2.445E+00	2.185E-02	2.164E+01	.7	10.4	39.30	48326	588.0	11374	4517	22
1.800E+00	3.305E+00	2.996E+00	2.966E-01	8.522E-01	1.349E-02	9.265E+00	1.1	3.6	39.30	48326	588.0	11374	4517	22
5.200E+00	9.185E+00	3.961E+00	1.592E+00	2.445E+00	2.185E-02	2.244E+01	.7	10.4	39.30	93274	588.0	11374	4517	22
1.800E+00	3.305E+00	2.996E+00	5.724E-01	8.522E-01	1.349E-02	9.535E+00	1.1	3.6	39.30	93274	588.0	11374	4517	22
5.200E+00	9.185E+00	3.961E+00	8.250E-01	1.076E+00	1.201E-02	2.024E+01	.7	10.4	114.40	48326	216.0	4214	4517	22
1.800E+00	3.305E+00	2.996E+00	2.966E-01	3.748E-01	7.409E-03	8.775E+00	1.1	3.6	114.40	48326	216.0	4214	4517	22
5.200E+00	9.185E+00	3.961E+00	1.592E+00	1.076E+00	1.201E-02	2.104E+01	.7	10.4	114.40	93274	216.0	4214	4517	22
1.800E+00	3.305E+00	2.996E+00	5.724E-01	3.748E-01	7.409E-03	9.055E+00	1.1	3.6	114.40	93274	216.0	4214	4517	22
5.200E+00	9.185E+00	3.961E+00	8.250E-01	2.220E+00	1.201E-02	2.144E+01	.7	10.4	114.40	48326	588.0	4214	4517	22
1.800E+00	3.305E+00	2.996E+00	2.966E-01	7.746E-01	7.409E-03	9.175E+00	1.1	3.6	114.40	48326	588.0	4214	4517	22
5.200E+00	9.185E+00	3.961E+00	1.592E+00	2.220E+00	1.201E-02	2.214E+01	.7	10.4	114.40	93274	588.0	4214	4517	22
1.800E+00	3.305E+00	2.996E+00	5.724E-01	7.746E-01	7.409E-03	9.455E+00	1.1	3.6	114.40	93274	588.0	4214	4517	22
5.200E+00	9.185E+00	3.961E+00	8.250E-01	1.076E+00	2.185E-02	2.024E+01	.7	10.4	114.40	48326	216.0	11374	4517	22
1.800E+00	3.305E+00	2.996E+00	2.966E-01	3.748E-01	1.349E-02	8.785E+00	1.1	3.6	114.40	48326	216.0	11374	4517	22
5.200E+00	9.185E+00	3.961E+00	1.592E+00	1.076E+00	2.185E-02	2.104E+01	.7	10.4	114.40	93274	216.0	11374	4517	22
1.800E+00	3.305E+00	2.996E+00	5.724E-01	3.748E-01	1.349E-02	9.065E+00	1.1	3.6	114.40	93274	216.0	11374	4517	22
5.200E+00	9.185E+00	3.961E+00	8.250E-01	2.220E+00	2.185E-02	2.144E+01	.7	10.4	114.40	48326	588.0	11374	4517	22
1.800E+00	3.305E+00	2.996E+00	2.966E-01	7.746E-01	1.349E-02	9.185E+00	1.1	3.6	114.40	48326	588.0	11374	4517	22
5.200E+00	9.185E+00	3.961E+00	1.592E+00	2.220E+00	2.185E-02	2.214E+01	.7	10.4	114.40	93274	588.0	11374	4517	22
1.800E+00	3.305E+00	2.996E+00	5.724E-01	7.746E-01	1.349E-02	9.465E+00	1.1	3.6	114.40	93274	588.0	11374	4517	22
5.200E+00	9.185E+00	3.961E+00	8.250E-01	1.191E+00	2.423E-02	2.334E+01	.7	10.4	39.30	48326	216.0	4214	13265	22
1.800E+00	3.305E+00	2.996E+00	2.366E-01	4.144E-01	1.493E-02	9.825E+00	1.1	3.6	39.30	48326	216.0	4214	13265	22

TABLE 14 (CONTD)

ACCIDENT-FREE MODEL DATA USED FOR SENSITIVITY ANALYSIS

TIME SPAN 4

Y(1)	Y(2)	Y(3)	Y(4)	Y(5)	Y(6)	Y(7)	F	TT	VSFPDT	FFDP	TFCNT	PD	SHOPFC	NFLP
5.200E+00	9.185E+00	3.961E+00	1.592E+00	1.191E+00	2.403E-02	2.114E+01	.7	10.4	39.30	93274	216.0	4214	13265	22
1.800E+00	3.305E+00	2.996E+00	5.724E-01	4.144E-01	1.483E-02	9.105E+00	1.1	3.6	39.30	93274	216.0	4214	13265	22
5.200E+00	9.185E+00	3.961E+00	8.250E-01	2.445E+00	2.403E-02	2.164E+01	.7	10.4	39.30	48326	588.0	4214	13265	22
1.800E+00	3.305E+00	2.996E+00	2.966E-01	8.522E-01	1.483E-02	9.265E+00	1.1	3.6	39.30	48326	588.0	4214	13265	22
5.200E+00	9.185E+00	3.961E+00	1.592E+00	2.445E+00	2.403E-02	2.244E+01	.7	10.4	39.30	93274	588.0	4214	13265	22
1.800E+00	3.305E+00	2.996E+00	5.724E-01	8.522E-01	1.483E-02	9.545E+00	1.1	3.6	39.30	93274	588.0	4214	13265	22
5.200E+00	9.185E+00	3.961E+00	8.250E-01	1.191E+00	3.388E-02	2.044E+01	.7	10.4	39.30	48326	216.0	11374	13265	22
1.800E+00	3.305E+00	2.996E+00	2.966E-01	4.144E-01	2.091E-02	8.835E+00	1.1	3.6	39.30	48326	216.0	11374	13265	22
5.200E+00	9.185E+00	3.961E+00	1.592E+00	1.191E+00	3.388E-02	2.114E+01	.7	10.4	39.30	93274	216.0	11374	13265	22
1.800E+00	3.305E+00	2.996E+00	5.724E-01	4.144E-01	2.091E-02	9.105E+00	1.1	3.6	39.30	93274	216.0	11374	13265	22
5.200E+00	9.185E+00	3.961E+00	8.250E-01	2.445E+00	3.388E-02	2.154E+01	.7	10.4	39.30	48326	588.0	11374	13265	22
1.800E+00	3.305E+00	2.996E+00	2.966E-01	8.522E-01	2.091E-02	9.275E+00	1.1	3.6	39.30	48326	588.0	11374	13265	22
5.200E+00	9.185E+00	3.961E+00	1.592E+00	2.445E+00	3.388E-02	2.244E+01	.7	10.4	39.30	93274	588.0	11374	13265	22
1.800E+00	3.305E+00	2.996E+00	5.724E-01	8.522E-01	2.091E-02	9.545E+00	1.1	3.6	39.30	93274	588.0	11374	13265	22
5.200E+00	9.185E+00	3.961E+00	8.250E-01	1.376E+00	2.403E-02	2.024E+01	.7	10.4	114.40	48326	216.0	4214	13265	22
1.800E+00	3.305E+00	2.996E+00	2.966E-01	3.748E-01	1.483E-02	8.785E+00	1.1	3.6	114.40	48326	216.0	4214	13265	22
5.200E+00	9.185E+00	3.961E+00	1.592E+00	1.076E+00	2.403E-02	2.104E+01	.7	10.4	114.40	93274	216.0	4214	13265	22
1.800E+00	3.305E+00	2.996E+00	5.724E-01	3.748E-01	1.483E-02	9.065E+00	1.1	3.6	114.40	93274	216.0	4214	13265	22
5.200E+00	9.185E+00	3.961E+00	8.250E-01	2.220E+00	2.403E-02	2.144E+01	.7	10.4	114.40	48326	588.0	4214	13265	22
1.800E+00	3.305E+00	2.996E+00	2.966E-01	7.746E-01	1.483E-02	9.185E+00	1.1	3.6	114.40	48326	588.0	4214	13265	22
5.200E+00	9.185E+00	3.961E+00	1.592E+00	2.220E+00	2.403E-02	2.214E+01	.7	10.4	114.40	93274	588.0	4214	13265	22
1.800E+00	3.305E+00	2.996E+00	5.724E-01	7.746E-01	1.483E-02	9.465E+00	1.1	3.6	114.40	93274	588.0	4214	13265	22
5.200E+00	9.185E+00	3.961E+00	8.250E-01	1.076E+00	3.388E-02	2.024E+01	.7	10.4	114.40	48326	216.0	11374	13265	22
1.800E+00	3.305E+00	2.996E+00	2.966E-01	3.748E-01	2.091E-02	8.795E+00	1.1	3.6	114.40	48326	216.0	11374	13265	22
5.200E+00	9.185E+00	3.961E+00	1.592E+00	1.076E+00	3.388E-02	2.104E+01	.7	10.4	114.40	93274	216.0	11374	13265	22
1.800E+00	3.305E+00	2.996E+00	5.724E-01	3.748E-01	2.091E-02	9.055E+00	1.1	3.6	114.40	93274	216.0	11374	13265	22
5.200E+00	9.185E+00	3.961E+00	8.250E-01	2.220E+00	3.388E-02	2.144E+01	.7	10.4	114.40	48326	588.0	11374	13265	22
1.800E+00	3.305E+00	2.996E+00	2.966E-01	7.746E-01	2.091E-02	9.195E+00	1.1	3.6	114.40	48326	588.0	11374	13265	22
5.200E+00	9.185E+00	3.961E+00	1.592E+00	2.220E+00	3.388E-02	2.224E+01	.7	10.4	114.40	93274	588.0	11374	13265	22
1.800E+00	3.305E+00	2.996E+00	5.724E-01	7.746E-01	2.091E-02	9.465E+00	1.1	3.6	114.40	93274	588.0	11374	13265	22
3.500E+00	6.318E+00	3.961E+00	8.309E-01	1.441E+00	3.316E-02	1.624E+01	.9	7.0	76.86	70800	402.0	7794	8891	15
0.	0.	0.	0.	0.	0.	0.	.9	0.0	76.86	70800	402.0	779.	8891	15
7.000E+00	1.264E+01	3.916E+00	1.652E+00	2.887E+00	6.632E-02	2.814E+01	.9	14.0	76.86	70800	402.0	779.	8891	15
3.500E+00	6.017E+00	3.961E+00	7.925E-01	1.432E+00	7.504E-03	1.575E+01	.5	7.0	76.86	70800	402.0	7794	8891	15
3.500E+00	6.511E+00	3.961E+00	8.558E-01	1.448E+00	4.745E-02	1.630E+01	1.3	7.0	76.86	70800	402.0	7794	8891	15
3.500E+00	6.318E+00	3.961E+00	8.309E-01	8.852E+00	3.316E-02	2.354E+01	.9	7.0	.62	70800	402.0	7794	8891	15
3.500E+00	6.318E+00	3.961E+00	8.309E-01	1.437E+00	3.316E-02	1.604E+01	.9	7.0	153.10	70800	402.0	7794	8891	15
3.500E+00	6.318E+00	3.961E+00	2.957E-01	1.441E+00	3.316E-02	1.554E+01	.9	7.0	76.86	25200	402.0	7794	8891	15
3.500E+00	6.318E+00	3.961E+00	1.366E+00	1.441E+00	3.316E-02	1.664E+01	.9	7.0	76.86	116400	402.0	7794	8891	15
3.500E+00	6.318E+00	3.961E+00	8.309E-01	1.721E-01	3.316E-02	1.484E+01	.9	7.0	76.86	70800	26.0	7794	8891	15
3.500E+00	6.318E+00	3.961E+00	8.309E-01	1.618E+00	3.316E-02	1.624E+01	.9	7.0	76.86	70800	779.0	7794	8891	15
3.500E+00	6.318E+00	3.961E+00	8.309E-01	1.441E+00	1.872E-02	1.604E+01	.9	7.0	76.86	70800	402.0	583	8891	15
3.500E+00	6.318E+00	3.961E+00	8.309E-01	1.441E+00	4.760E-02	1.614E+01	.9	7.0	76.86	70800	402.0	15058	8891	15
3.500E+00	6.318E+00	3.961E+00	8.309E-01	1.441E+00	1.552E-02	1.604E+01	.9	7.0	76.86	70800	402.0	7794	16	15
3.500E+00	6.318E+00	3.961E+00	8.309E-01	1.441E+00	5.080E-02	1.614E+01	.9	7.0	76.86	70800	402.0	7794	17766	15
3.500E+00	6.318E+00	3.961E+00	8.309E-01	1.441E+00	1.496E-01	1.624E+01	.9	7.0	76.86	70800	402.0	7794	8891	1
3.500E+00	6.318E+00	3.961E+00	8.309E-01	1.441E+00	1.728E-02	1.604E+01	.9	7.0	76.86	70800	402.0	7794	8891	29

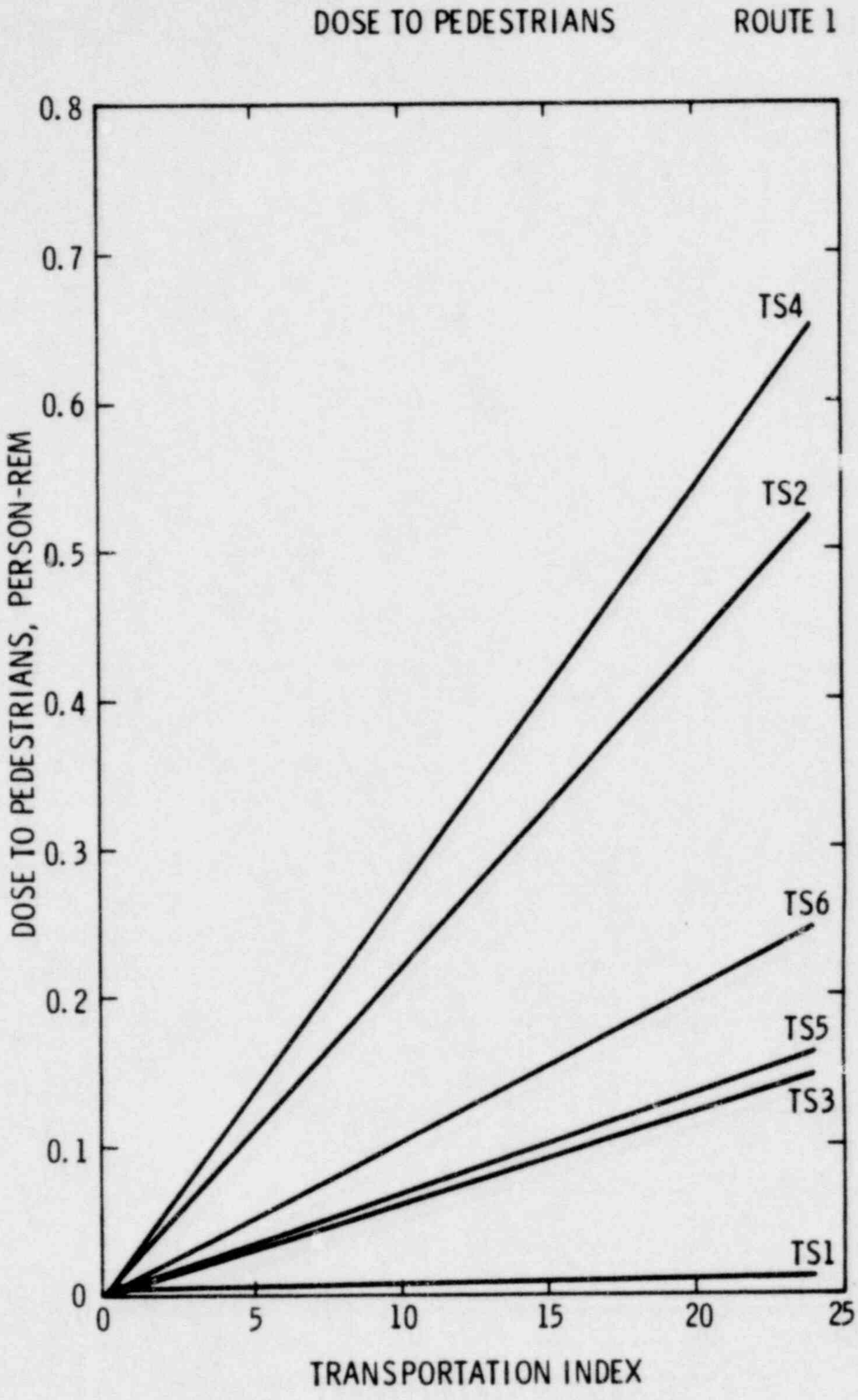


Figure 1. Dose to Pedestrians vs Transportation Index - Route 1

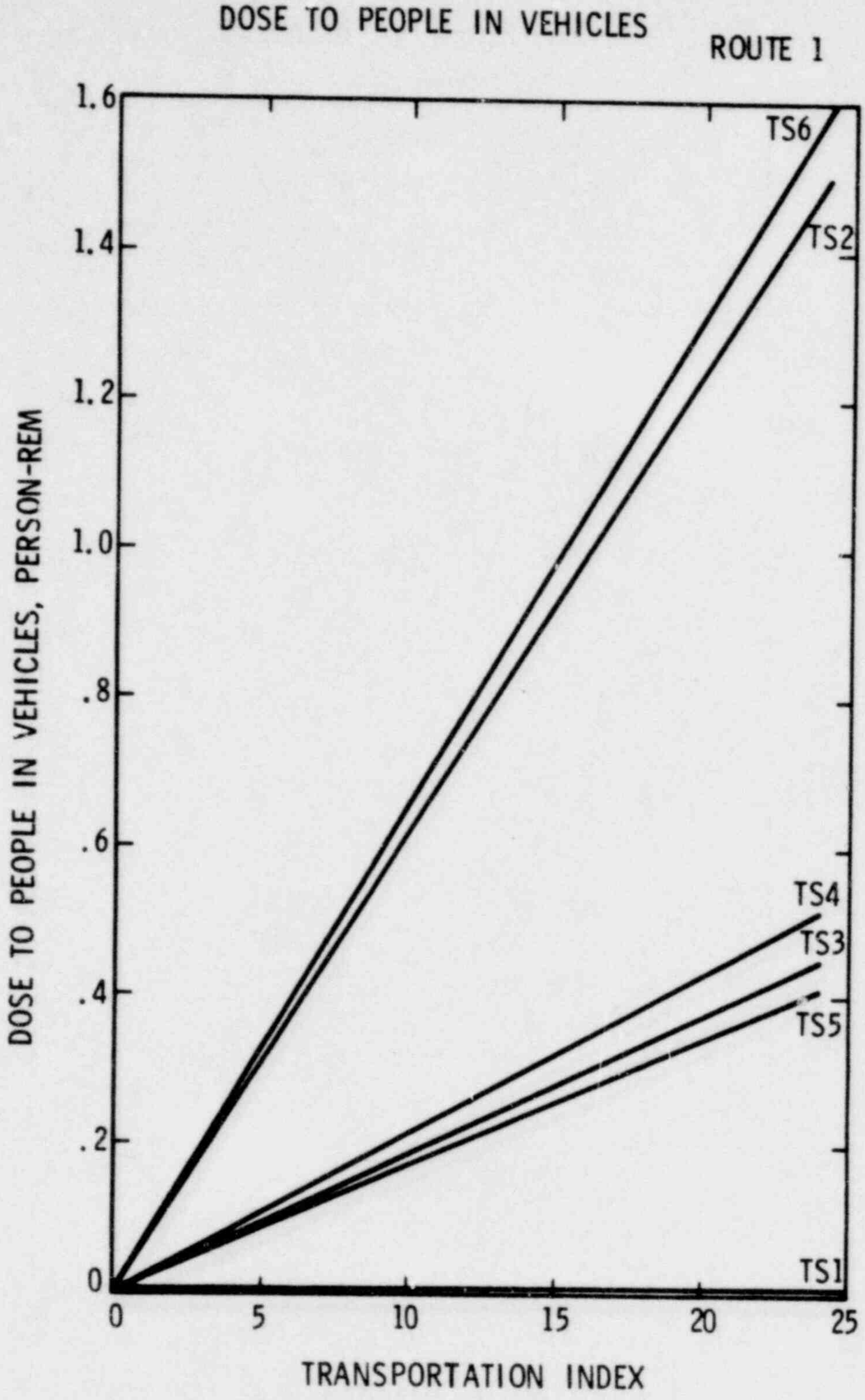


Figure 2. Dose to People in Vehicles vs Transportation Index - Route 1

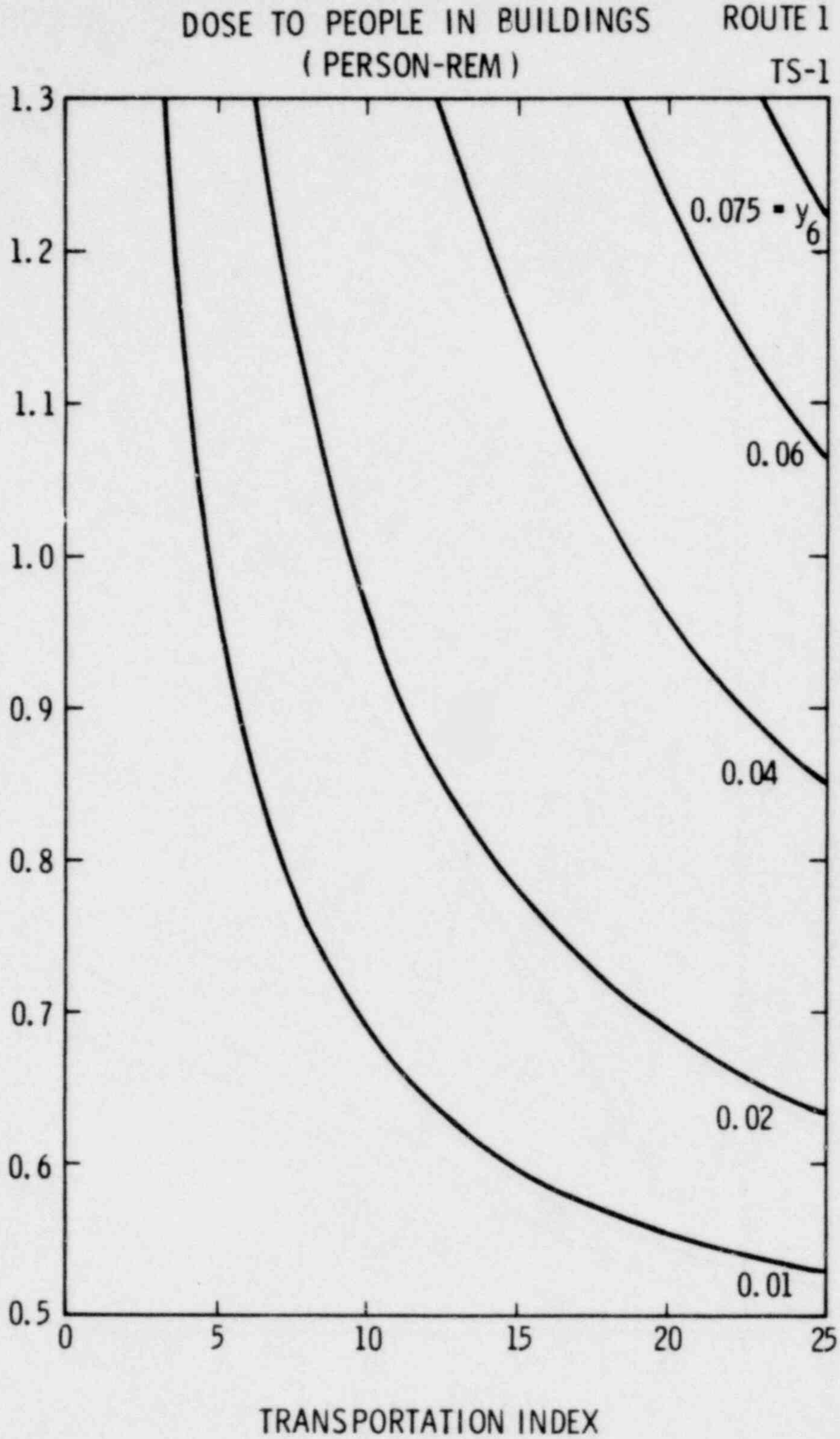


Figure 3. Contours of Constant Dose to People in Buildings - Route 1, TS-1

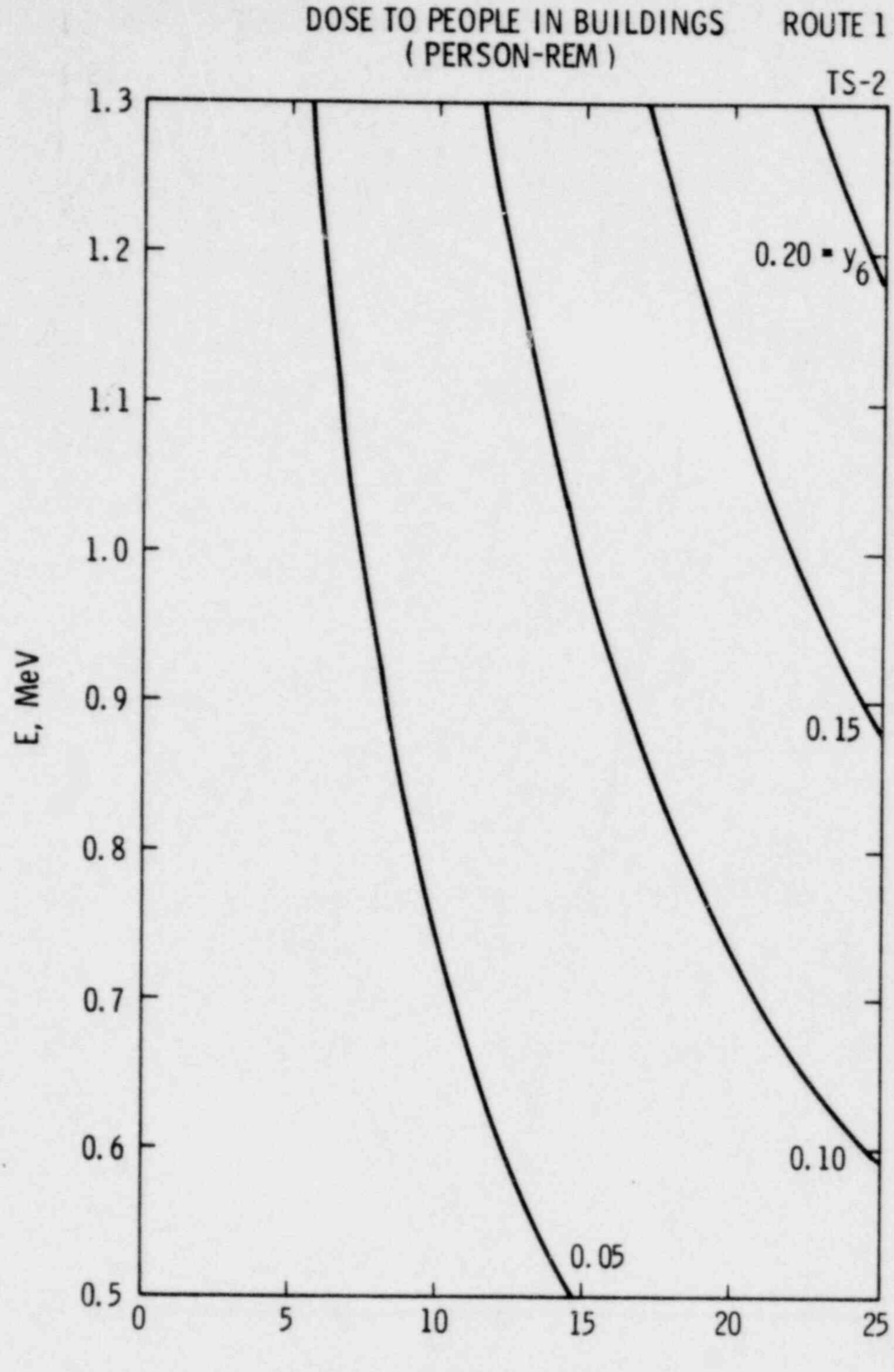


Figure 4. Contours of Constant Dose to People in Buildings - Route 1, TS-2

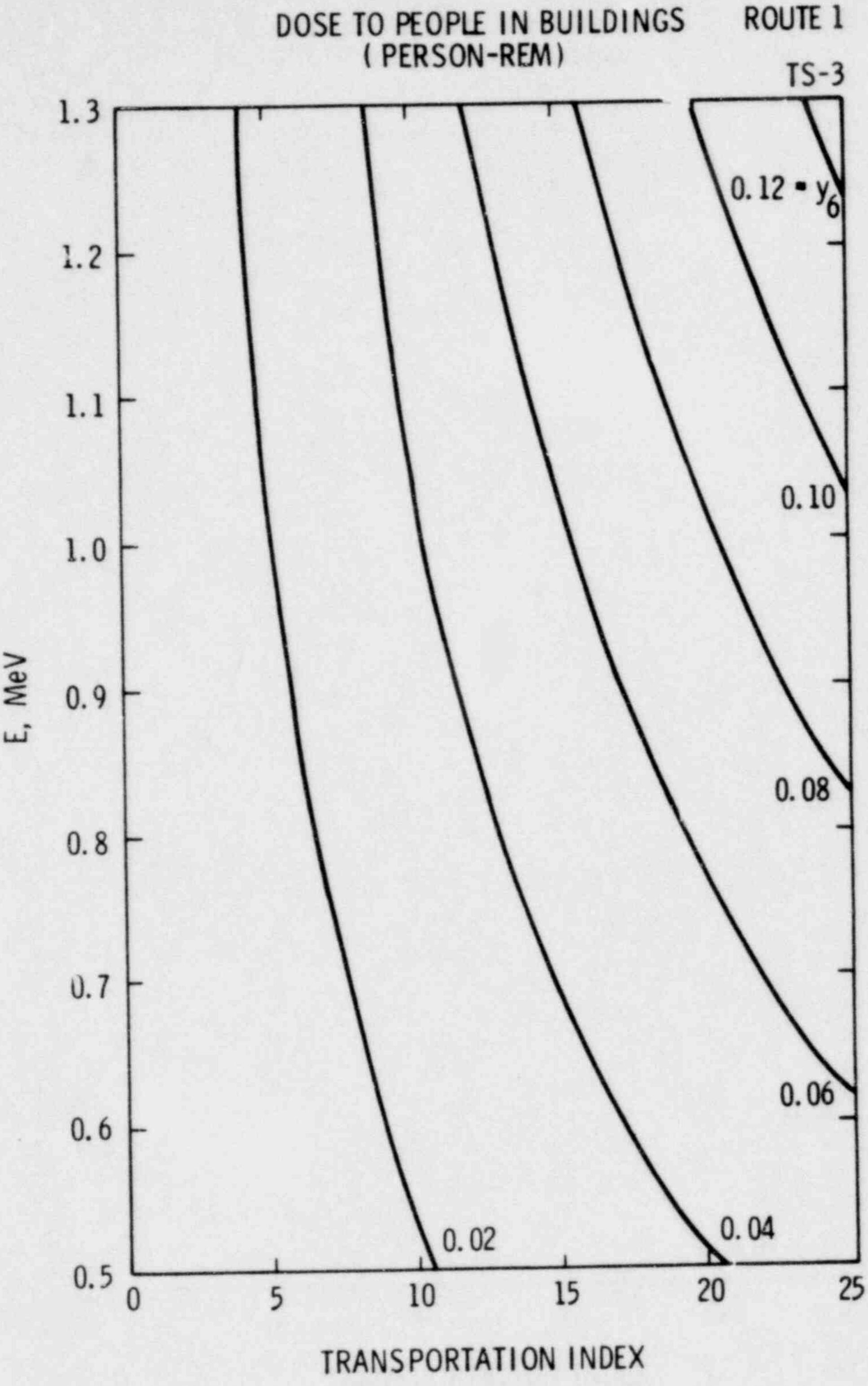


Figure 5. Contours of Constant Dose to People in Buildings - Route 1, TS-3

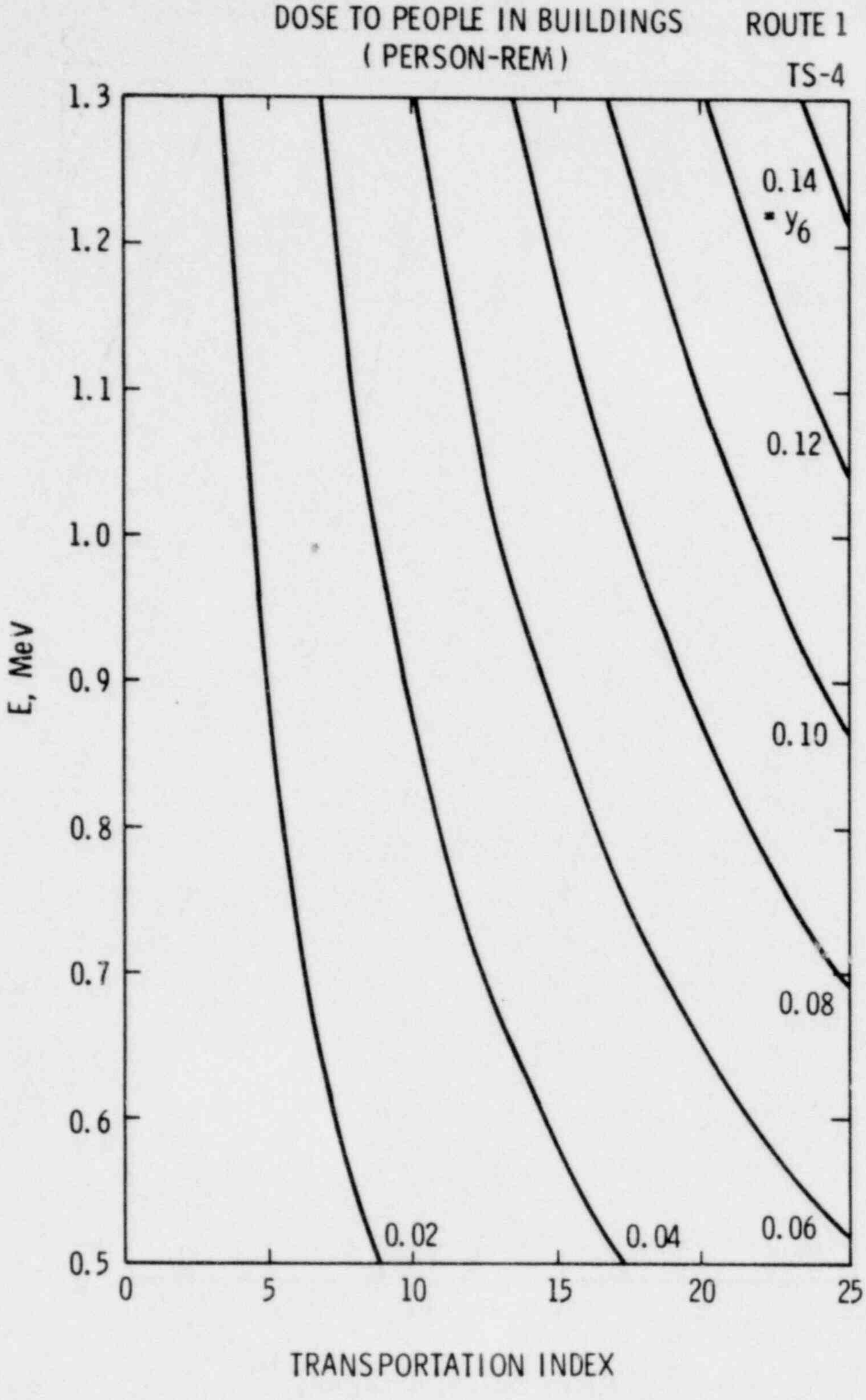


Figure 6. Contours of Constant Dose to People in Buildings - Route 1, TS-4

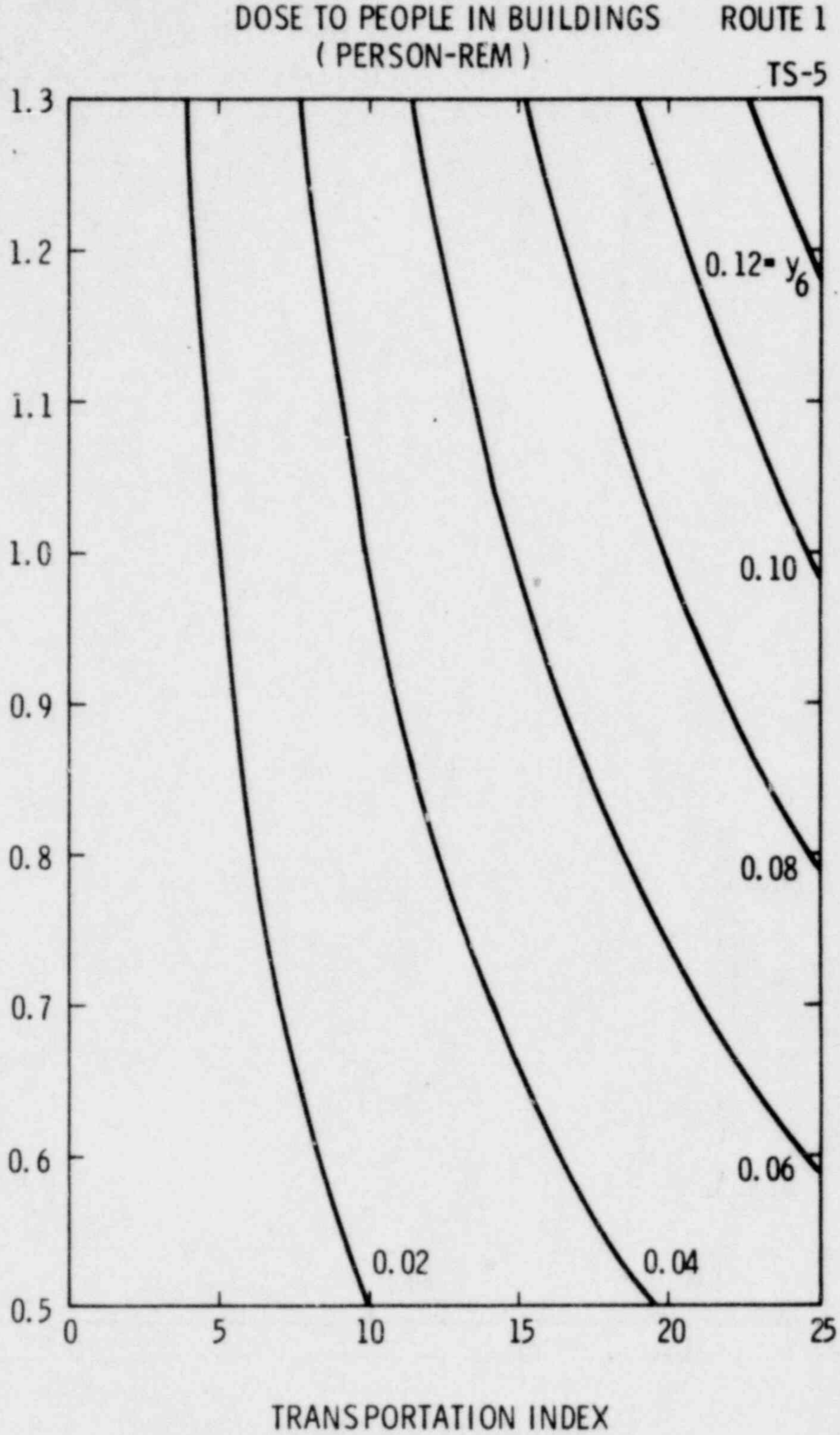


Figure 7. Contours of Constant Dose to People in Buildings - Route 1, TS-5

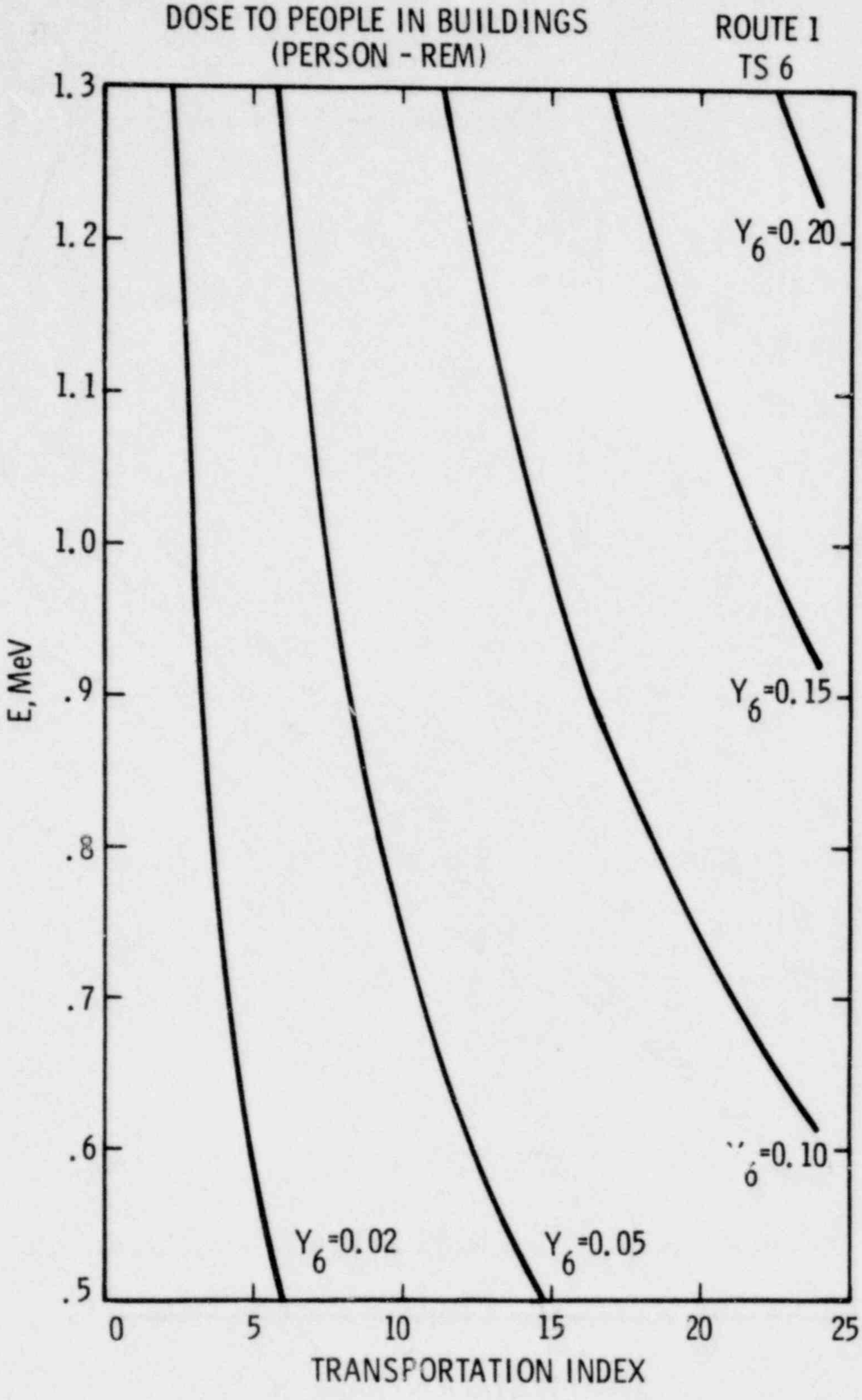


Figure 8. Contours of Constant Dose to People in Buildings - Route 1, TS-6

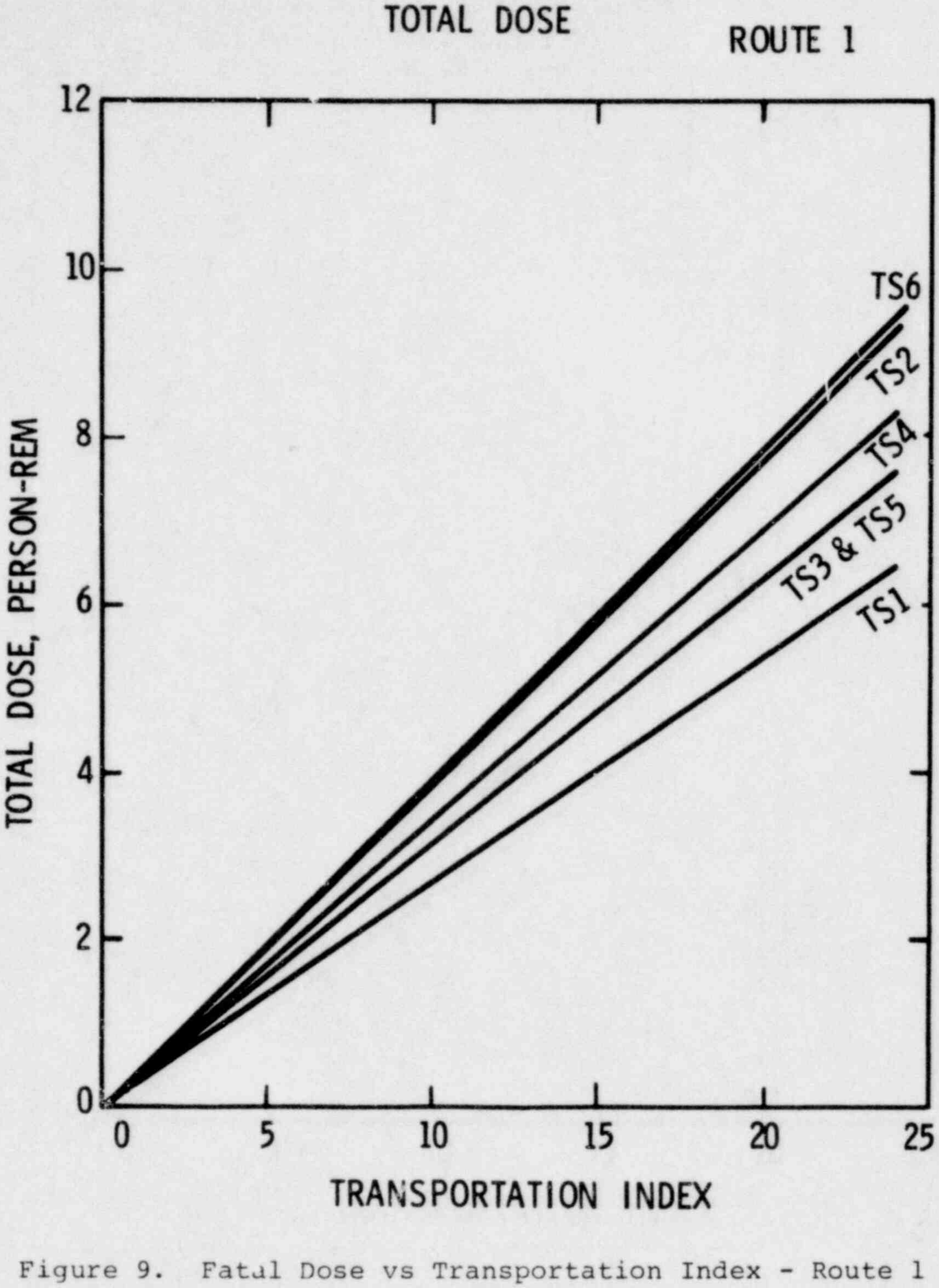


Figure 9. Fatal Dose vs Transportation Index - Route 1

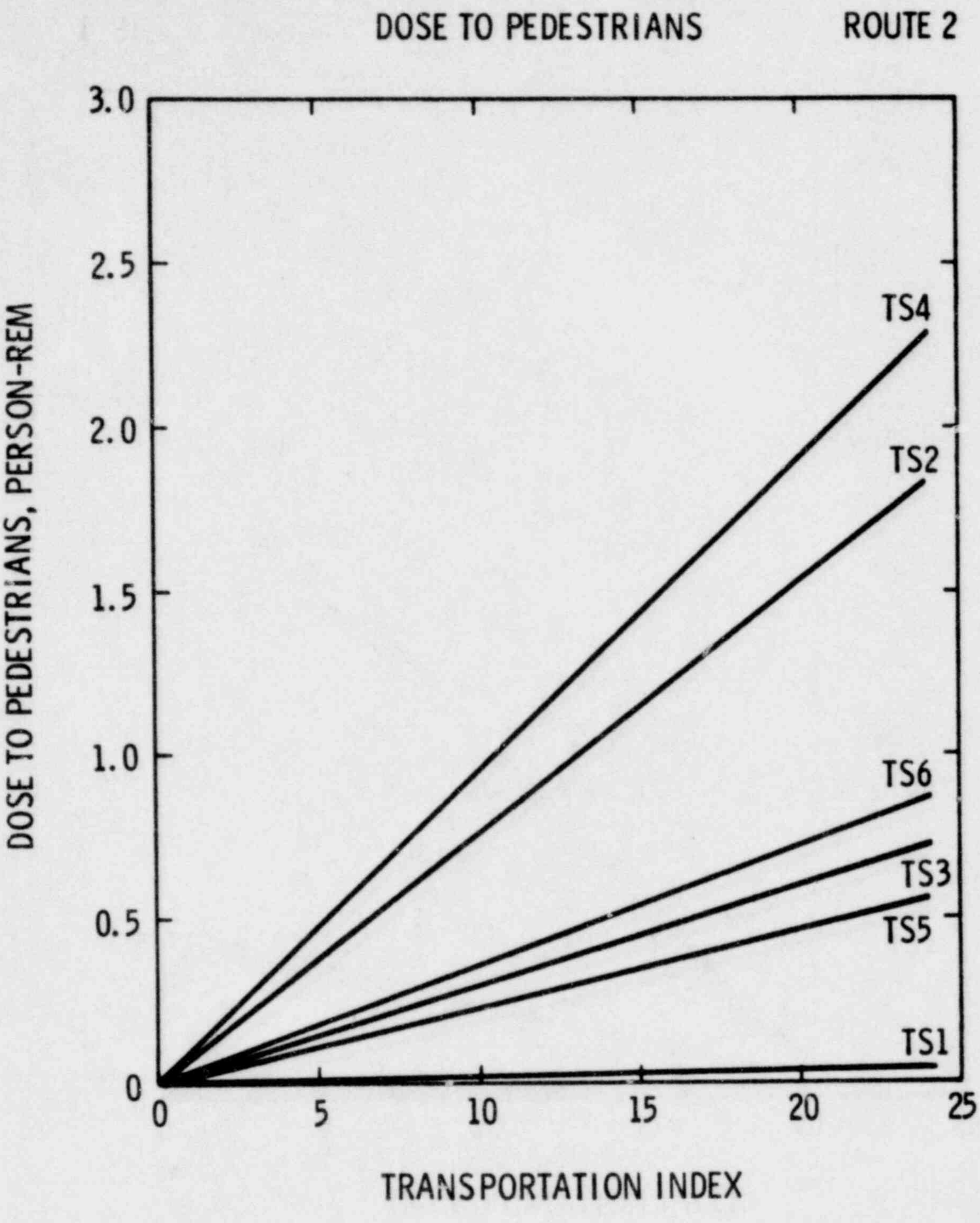


Figure 10. Dose to Pedestrians vs Transportation Index - Route 2

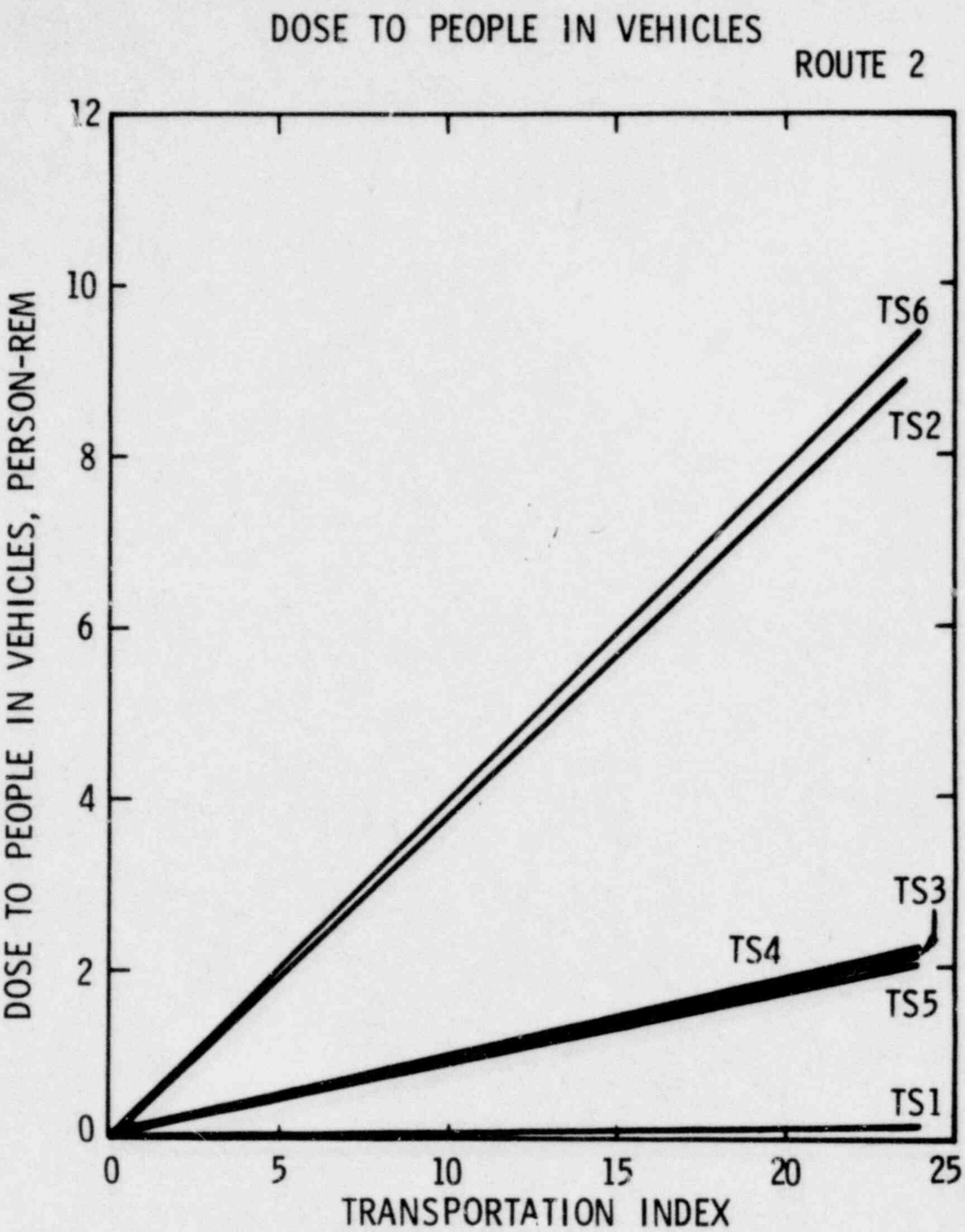


Figure 11. Dose to People in Vehicles vs Transportation Index - Route 2

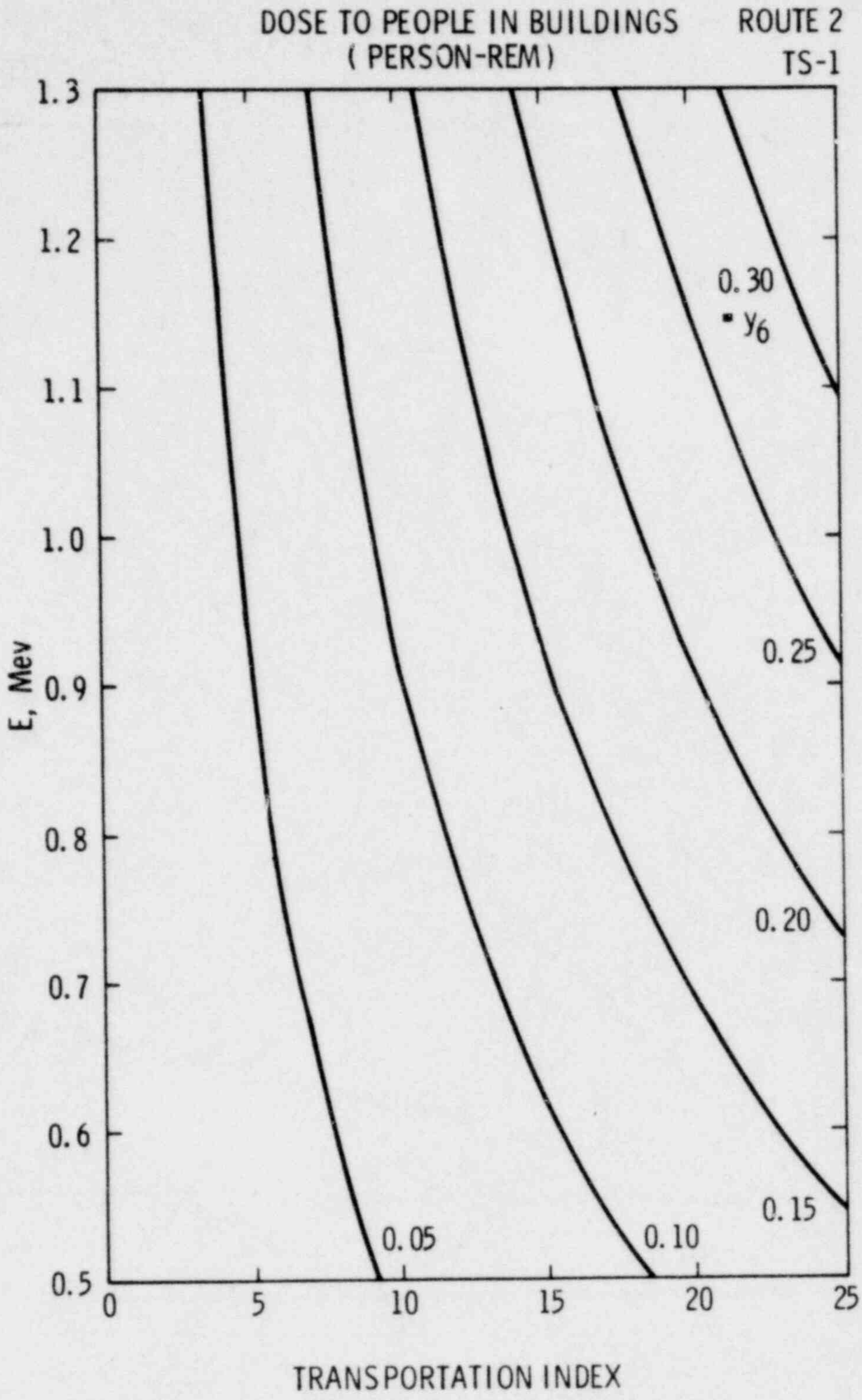


Figure 12. Contours of Constant Dose to People in Buildings - Route 2, TS-1

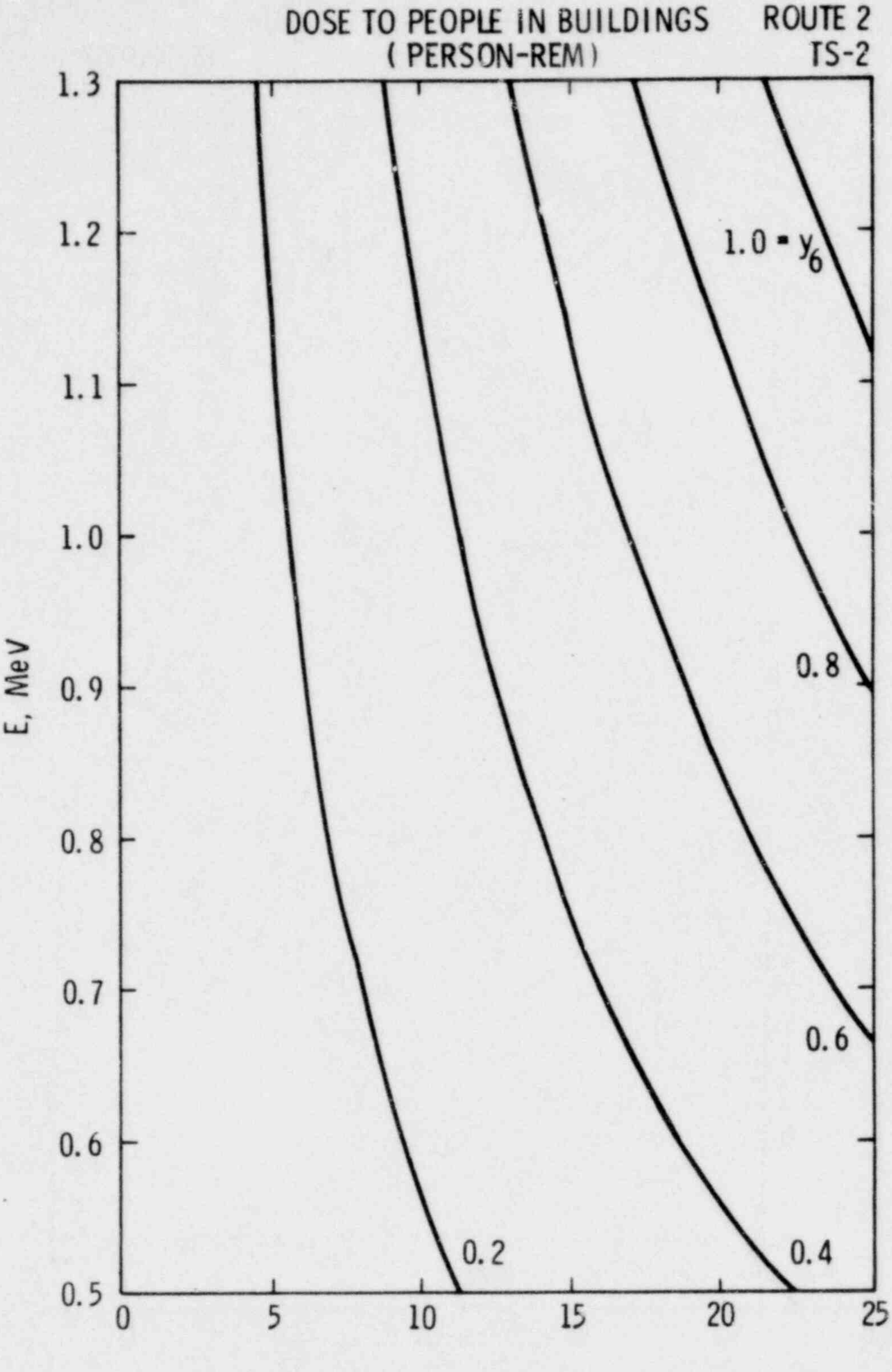


Figure 13. Contours of Constant Dose to People in Buildings - Route 2, TS-2

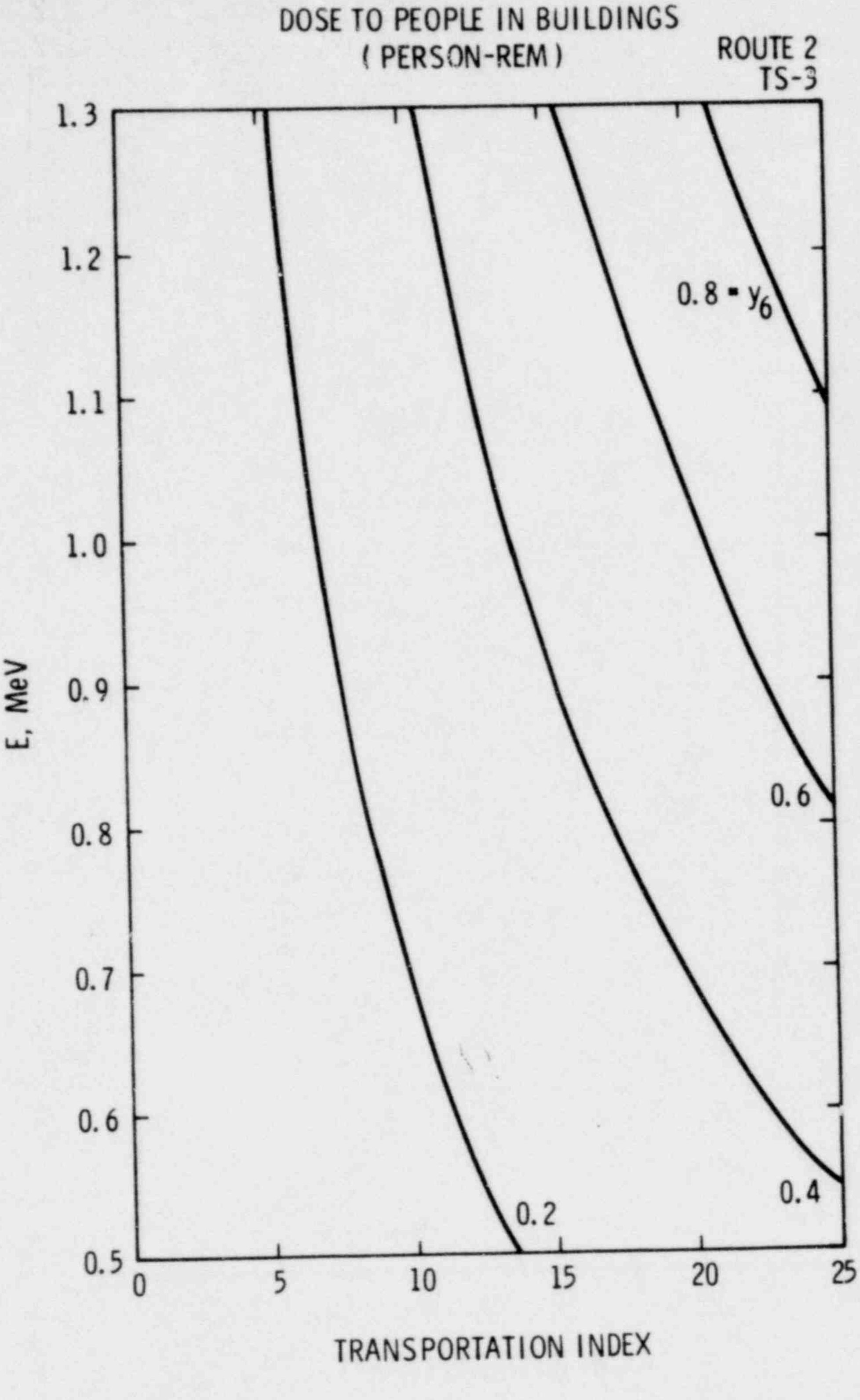


Figure 14. Contours of Constant Dose to People in Buildings - Route 2, TS-3

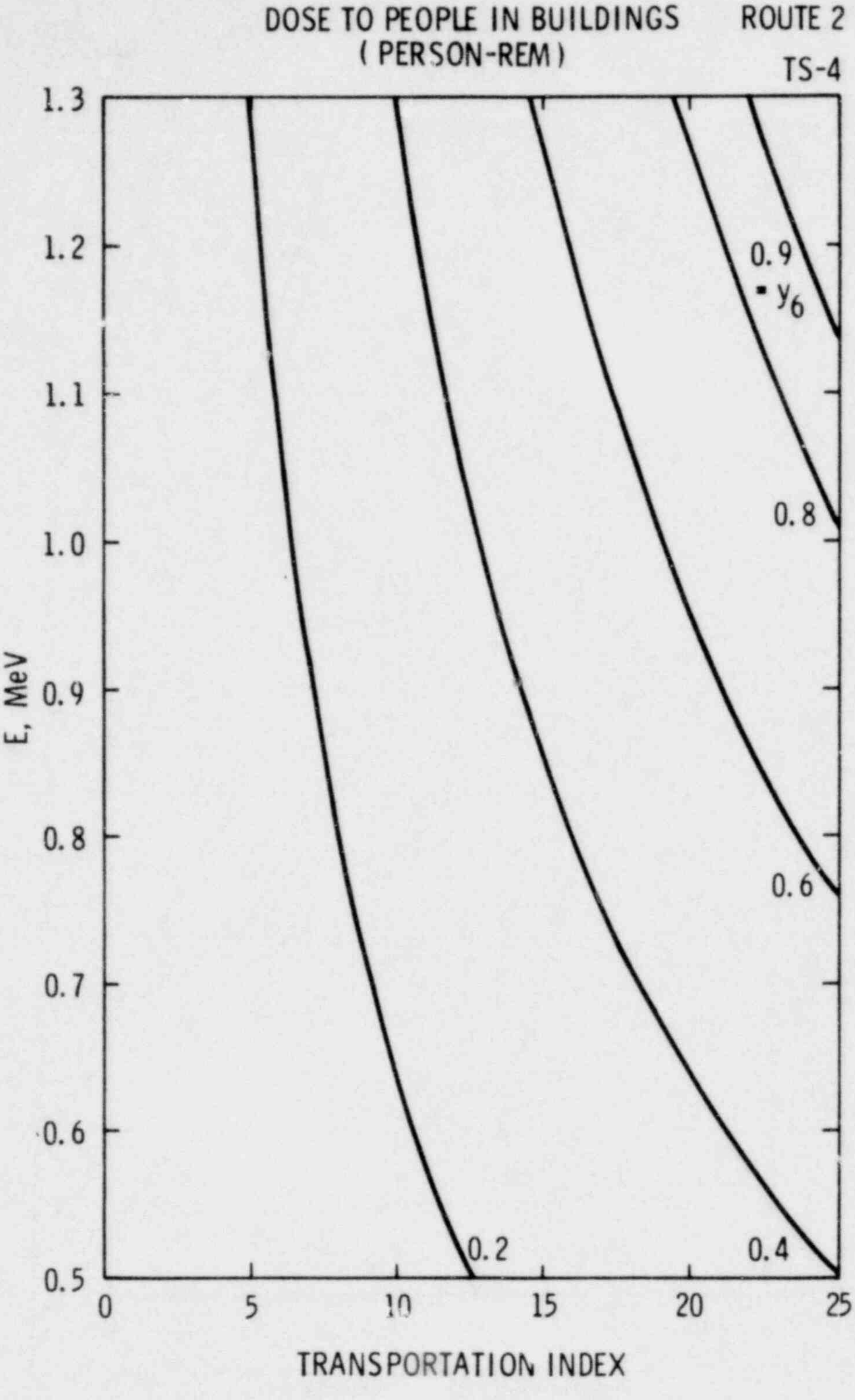


Figure 15. Contours of Constant Dose to People in Buildings - Route 2, TS-4

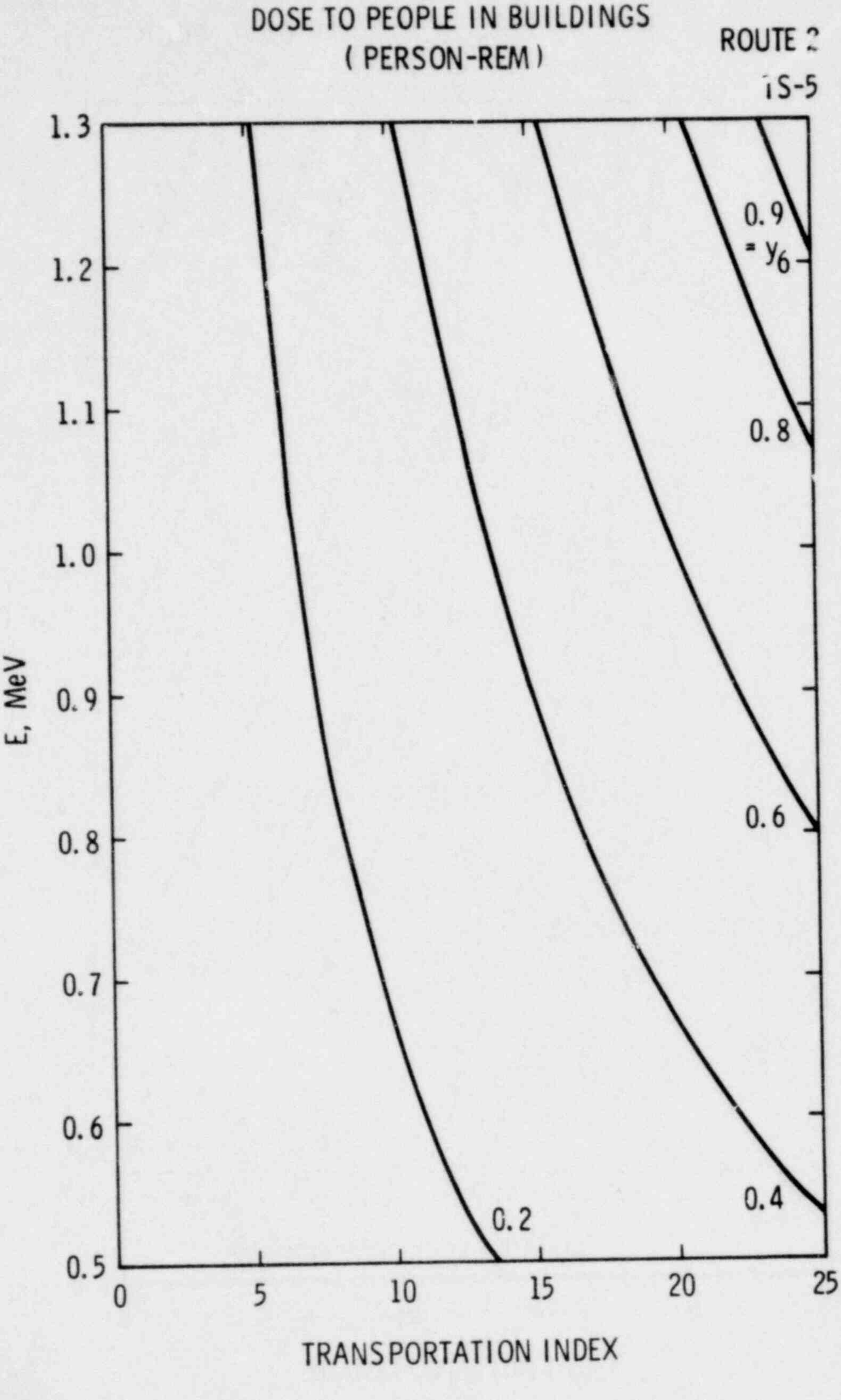


Figure 16. Contours of Constant Dose to People in Buildings - Route 2, TS-5

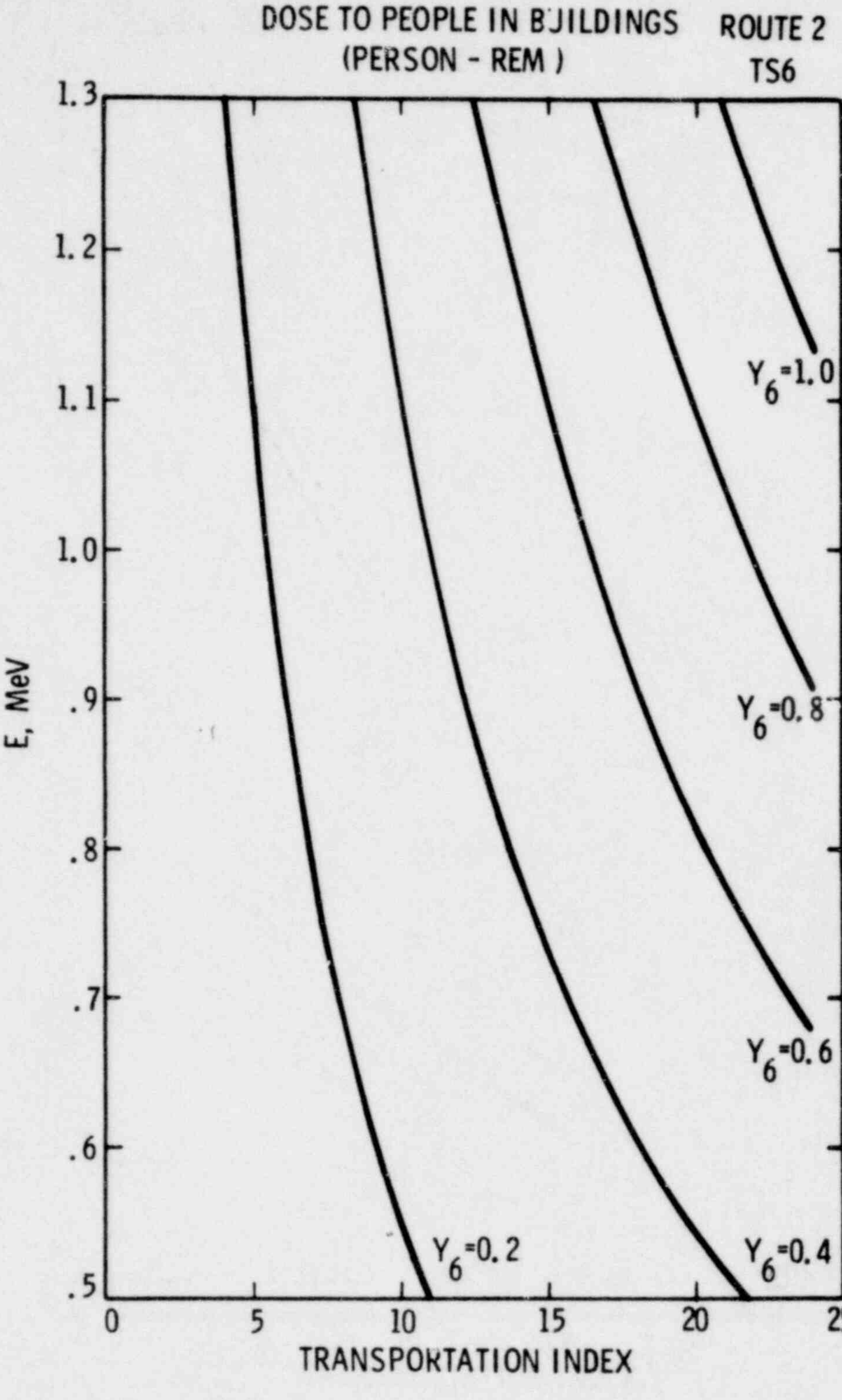


Figure 17. Contours of Constant Dose to People in Buildings - Route 2, TS-6

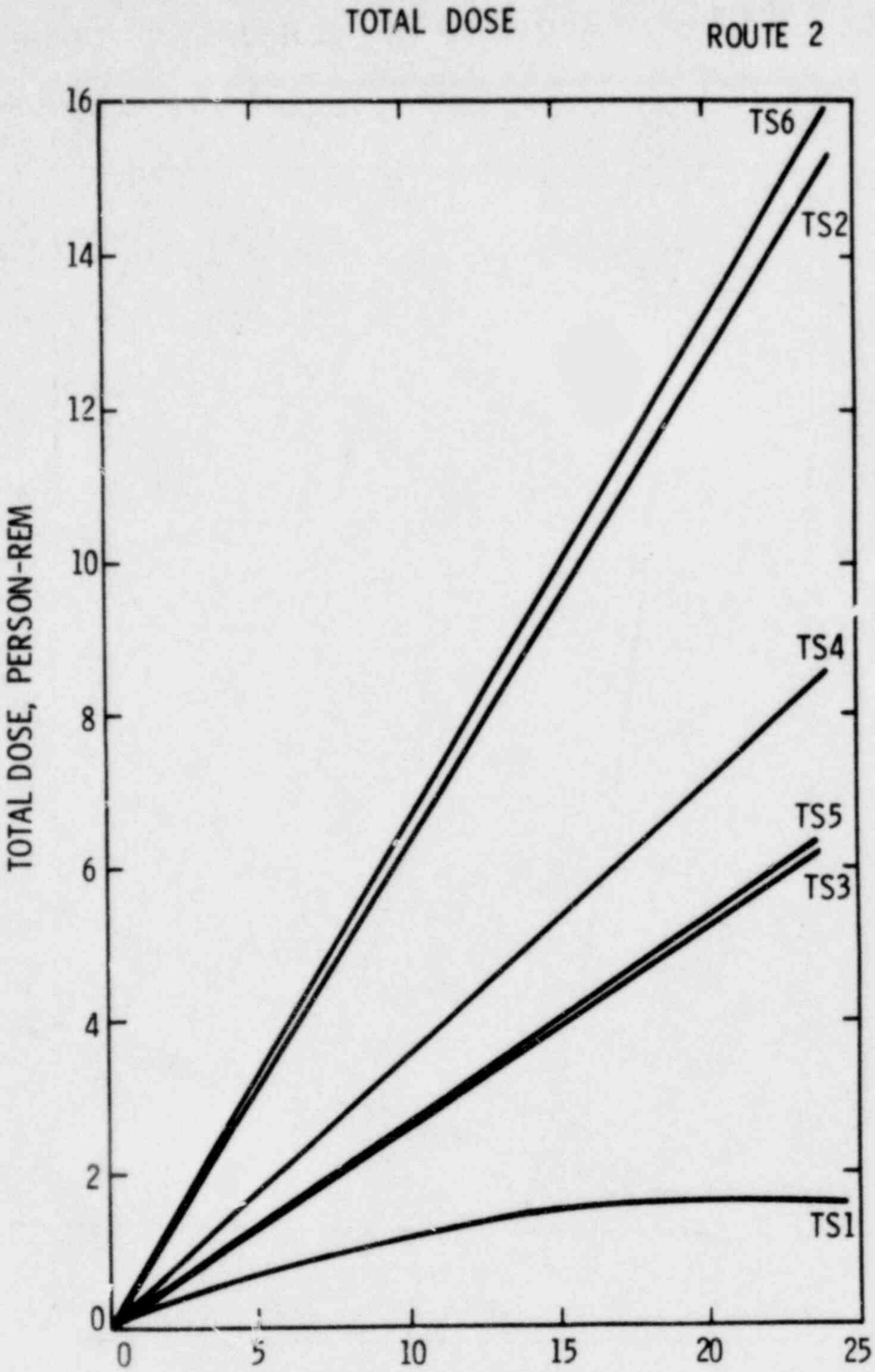


Figure 18. Total Dose vs Transportation Index - Route 2

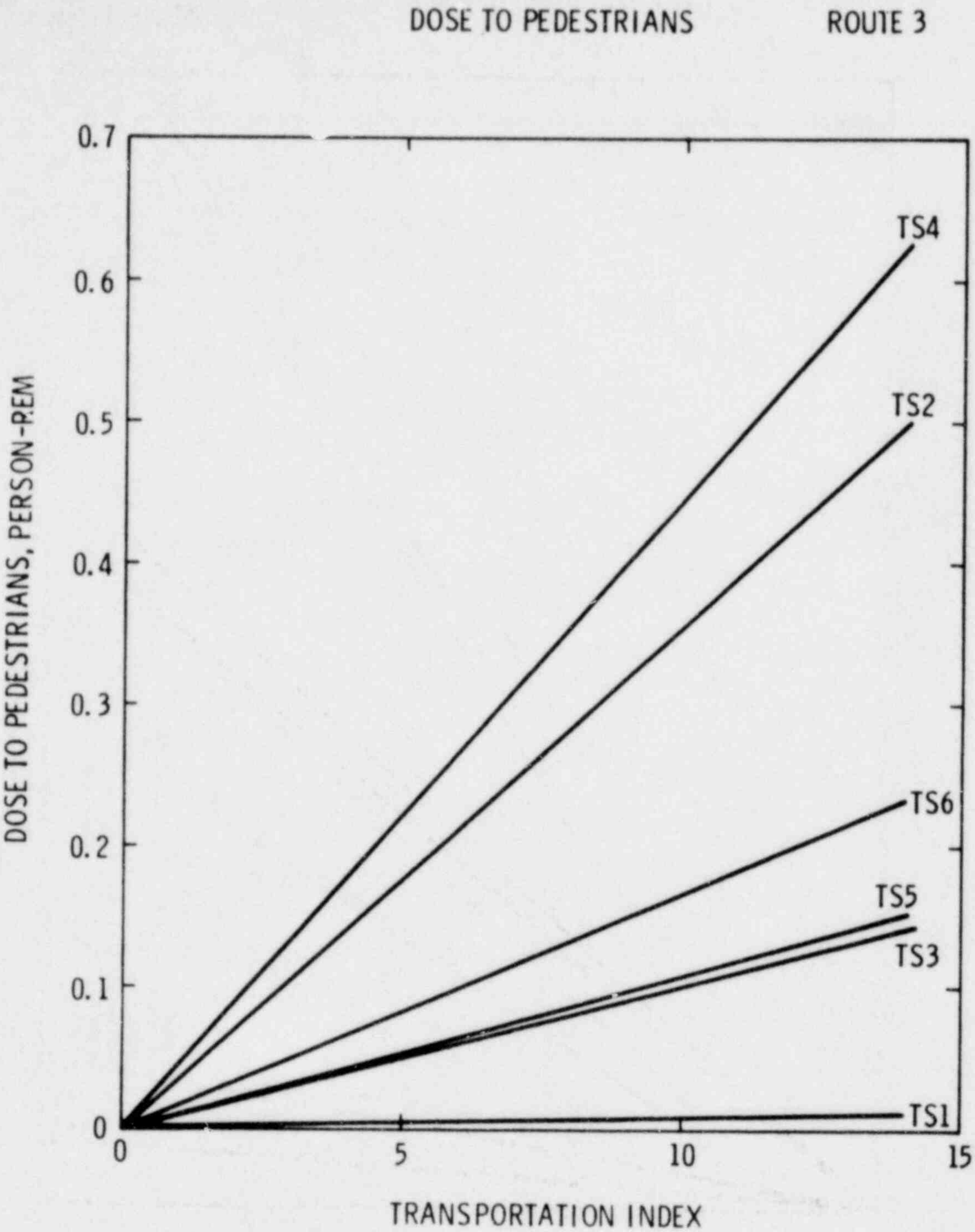


Figure 19. Dose to Pedestrians vs Transportation Index - Route 3

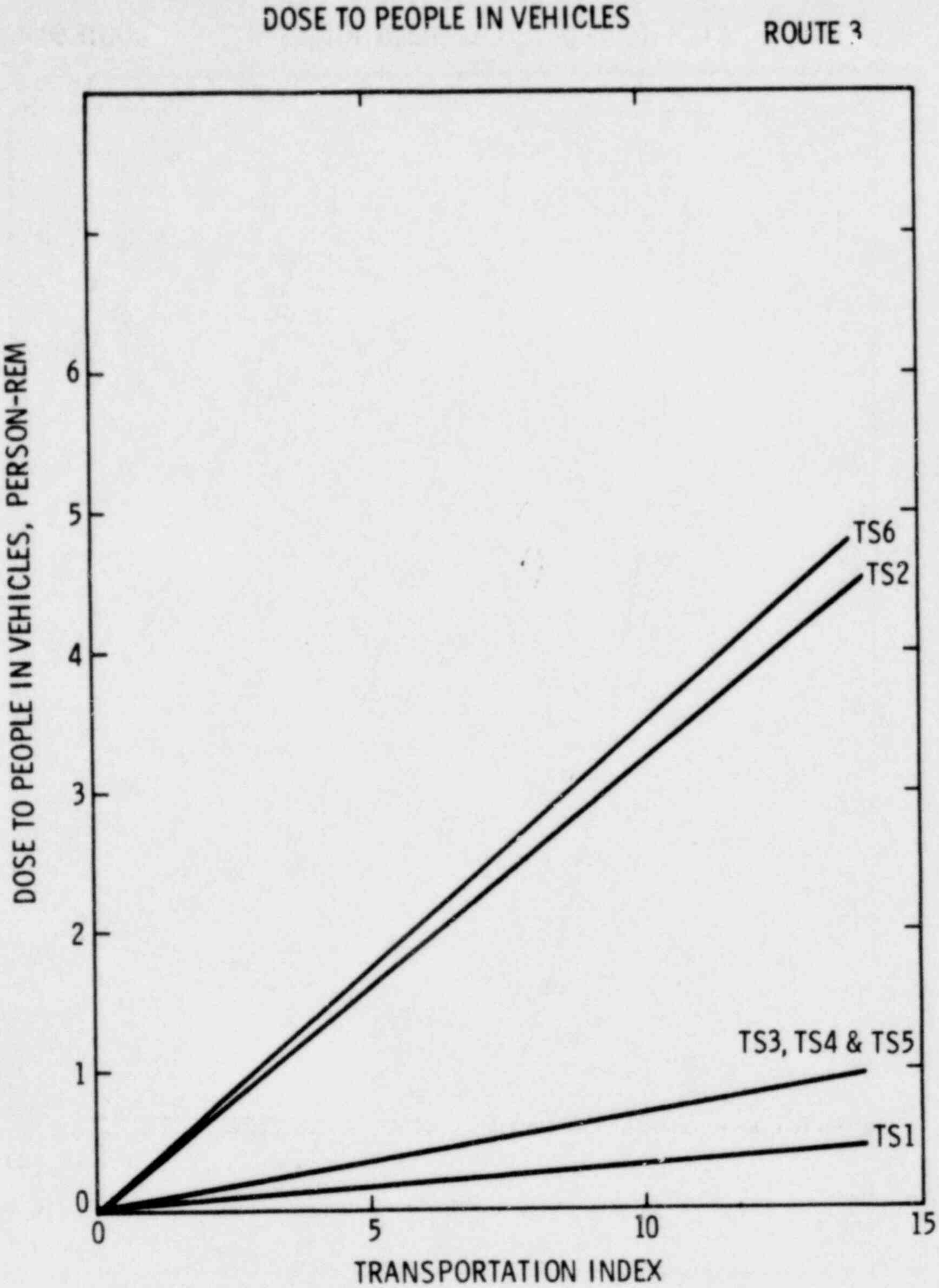


Figure 20. Dose to People in Vehicles vs Transportation Index - Route 3

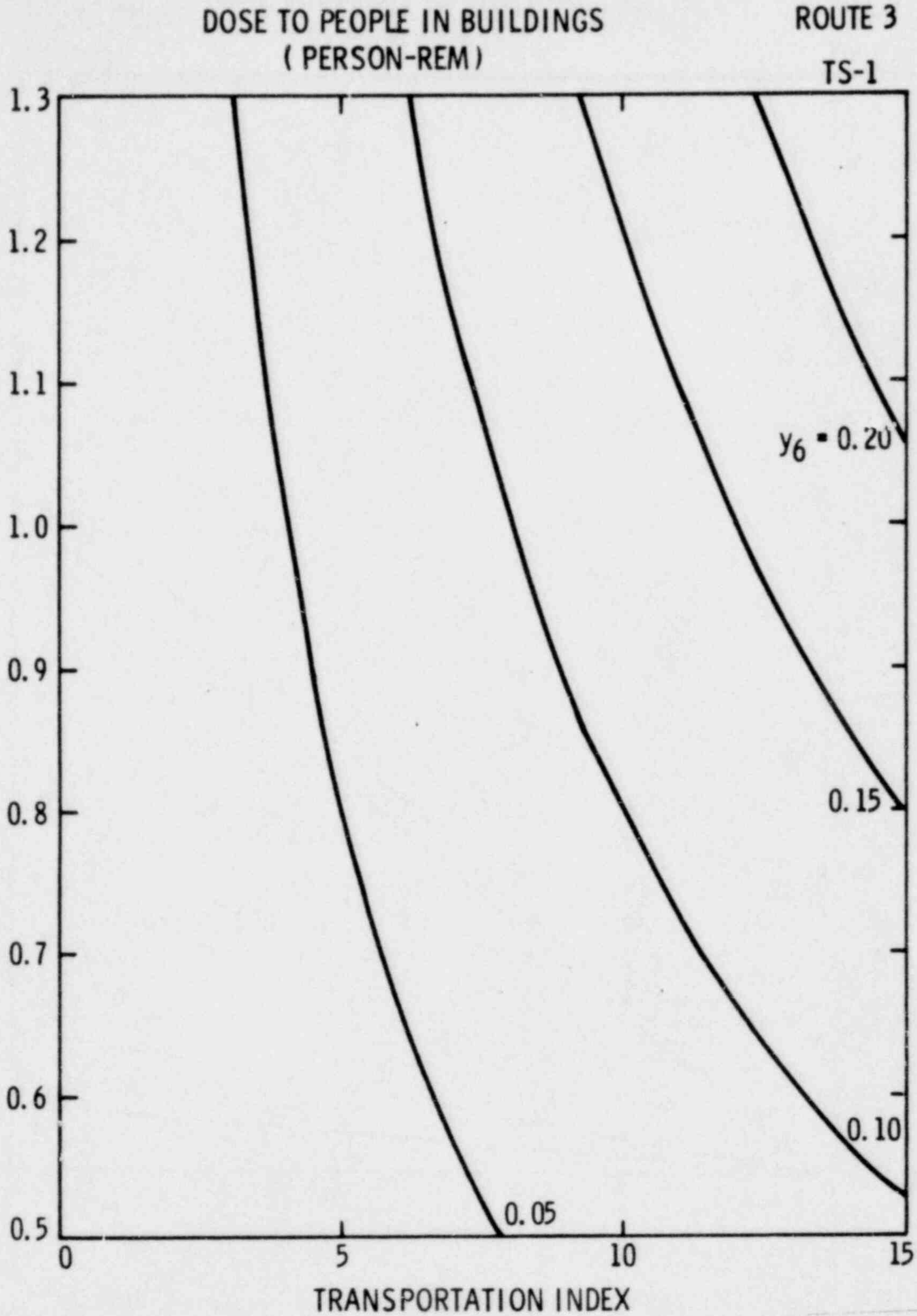


Figure 21. Contours of Constant Dose to People in Buildings - Route 3, TS-1

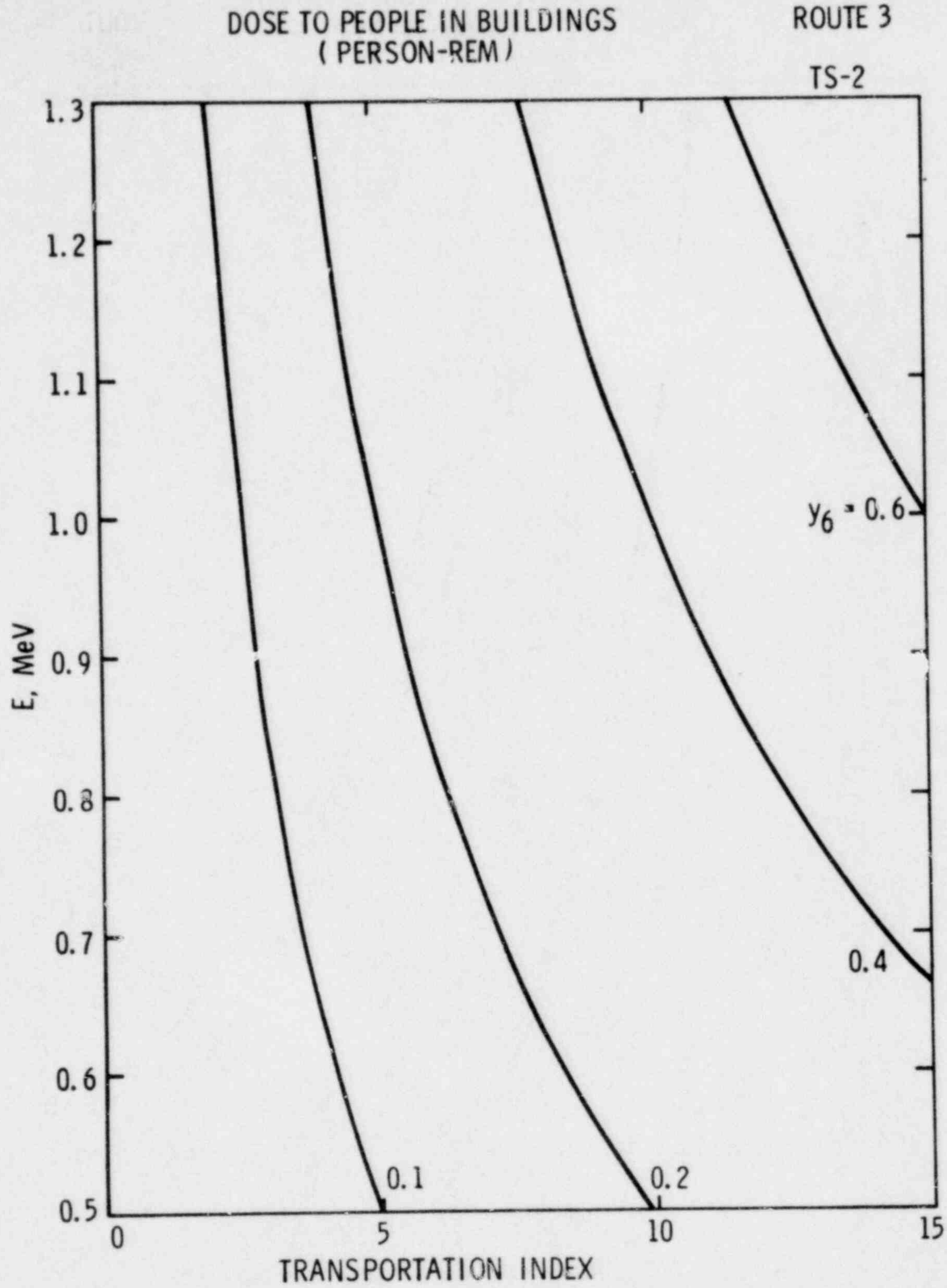


Figure 22. Contours of Constant Dose to People in Buildings - Route 3, TS-2

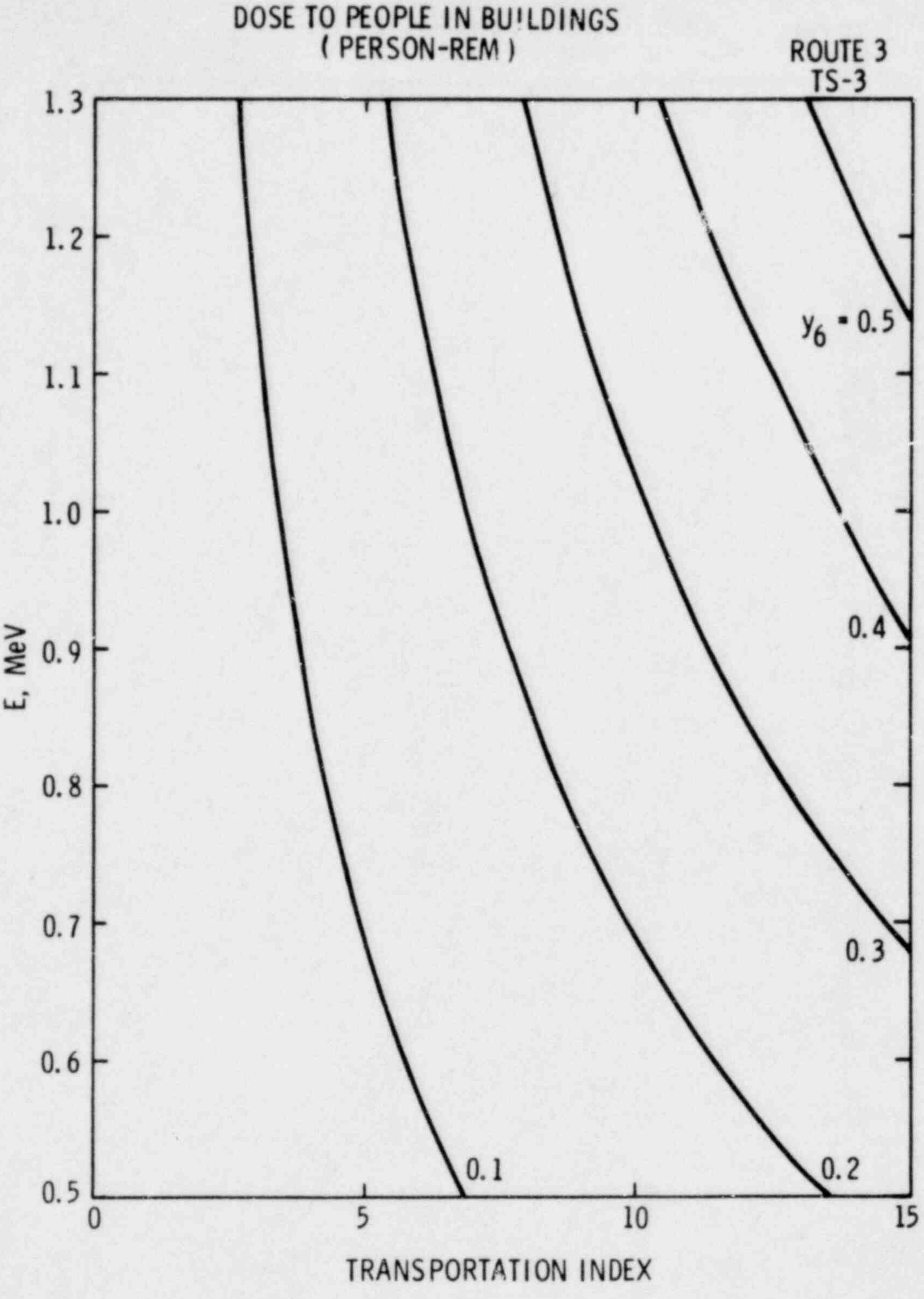


Figure 23. Contours of Constant Dose to People in Buildings - Route 3, TS-3

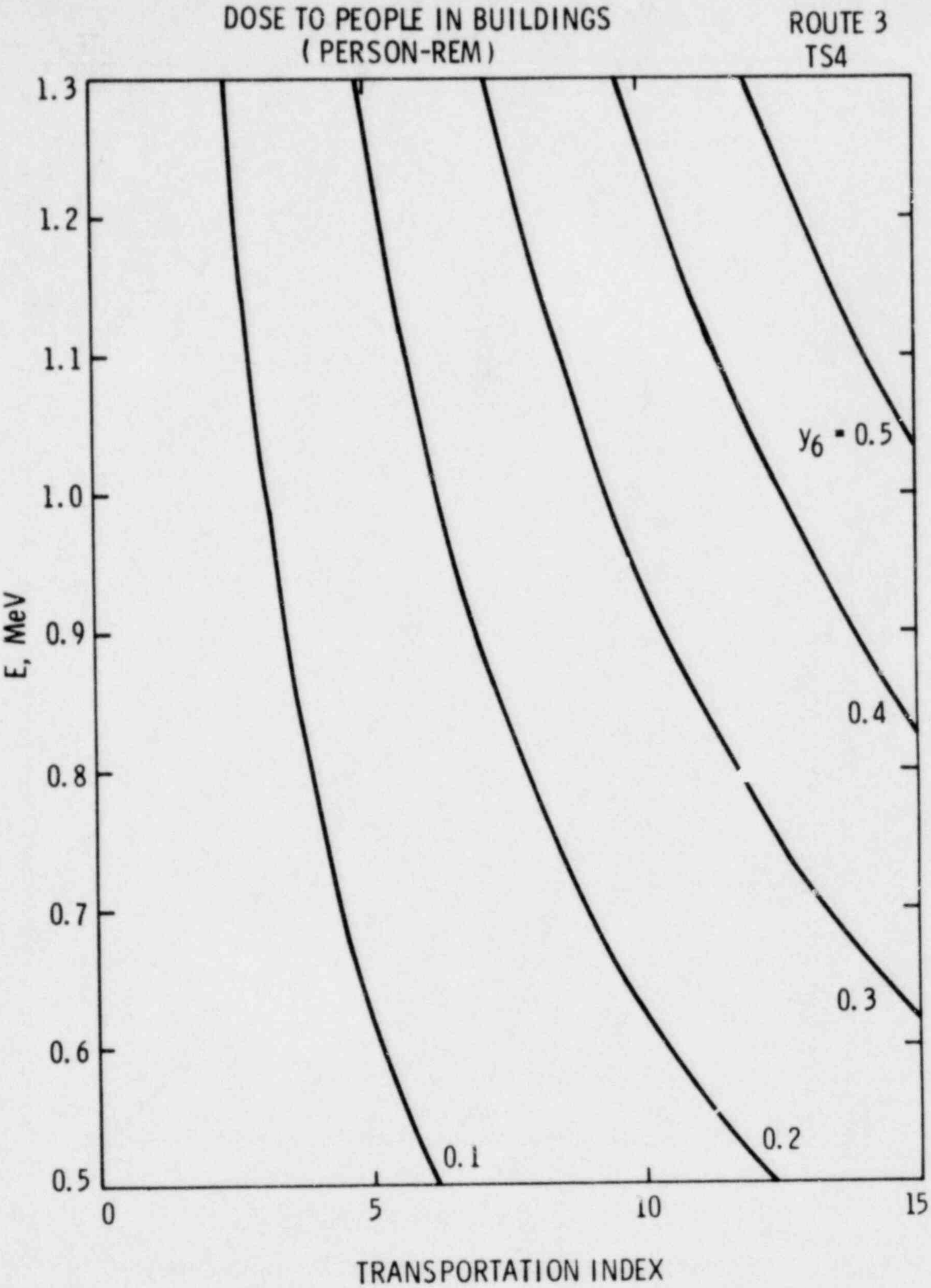


Figure 24. Contours of Constant Dose to People in Buildings - Route 3, TS-4

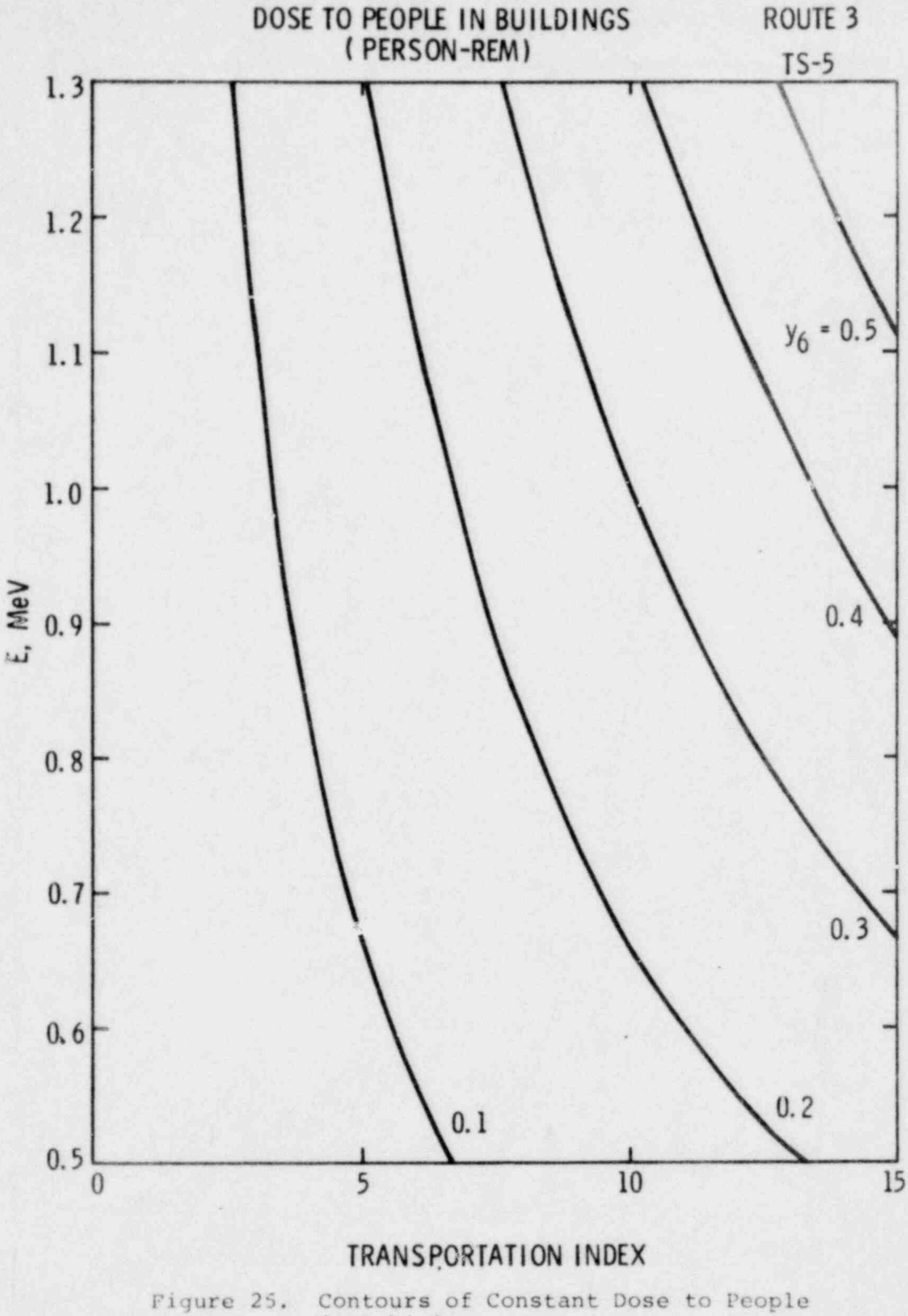


Figure 25. Contours of Constant Dose to People in Behicles

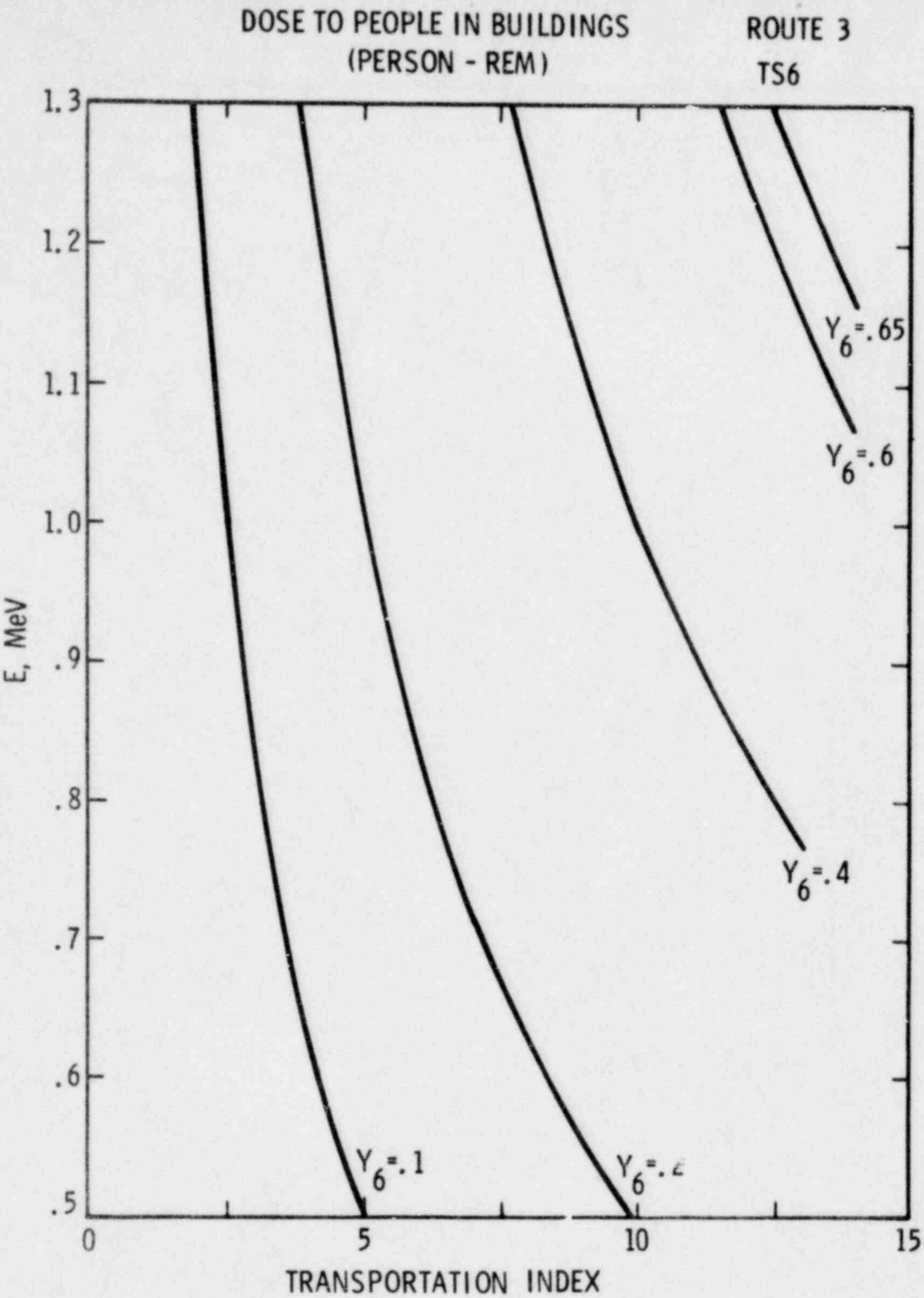


Figure 26. Contours of Constant Dose to People in Vehicles - Route 3, TS-6

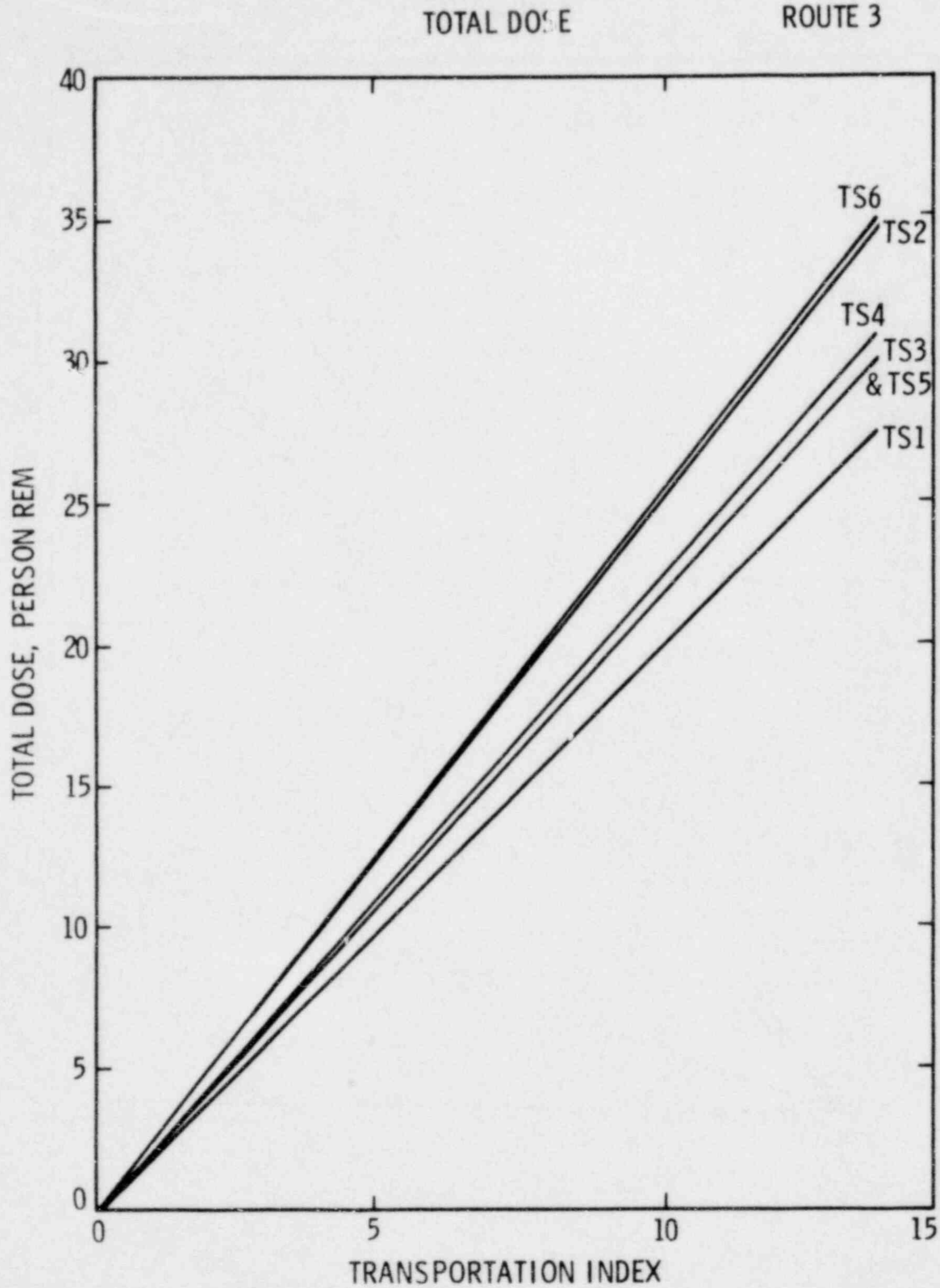


Figure 27. Total Dose vs Transportation Index - Route 3

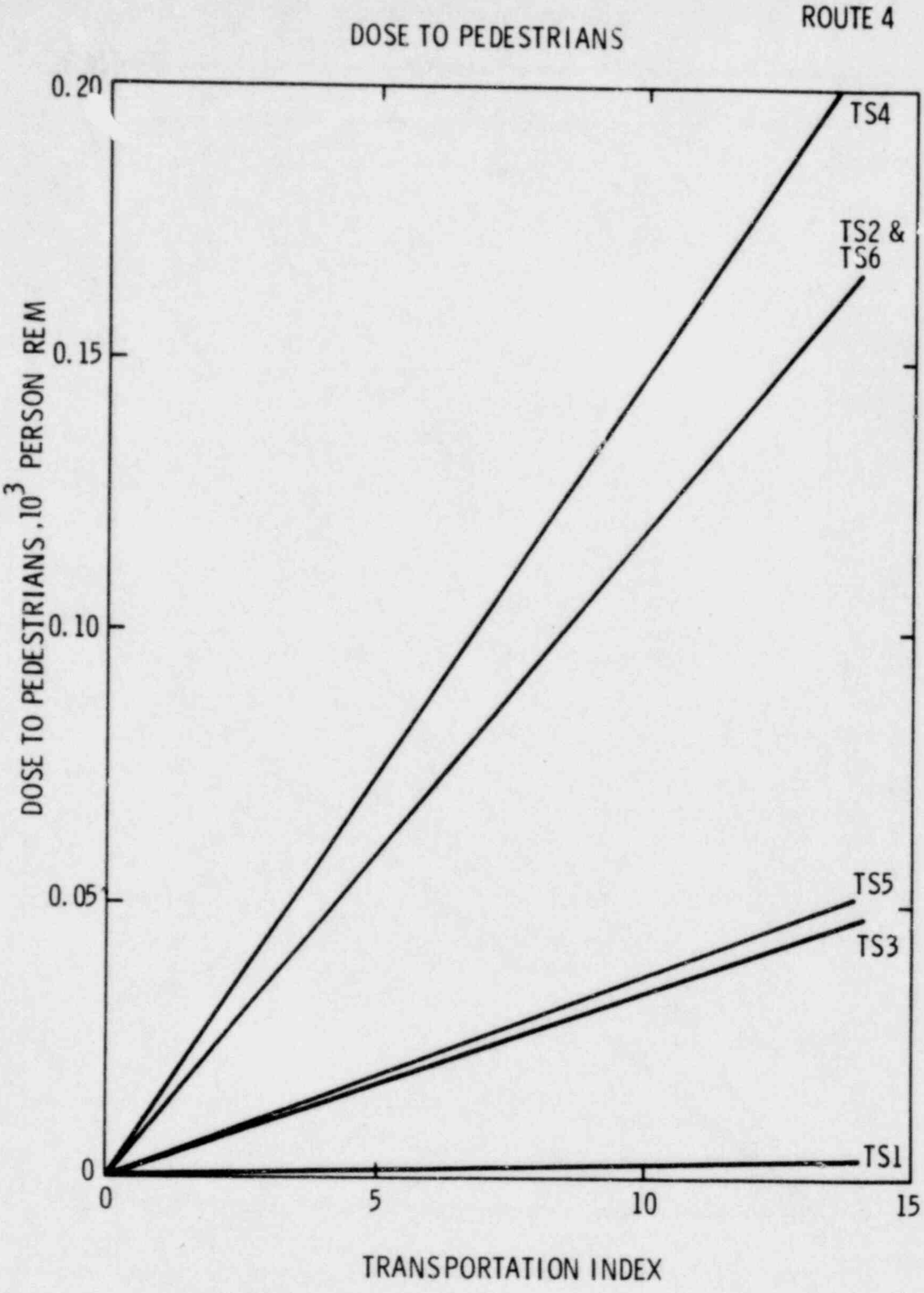


Figure 28. Dose to Pedestrians vs Transportation Index - Route 4

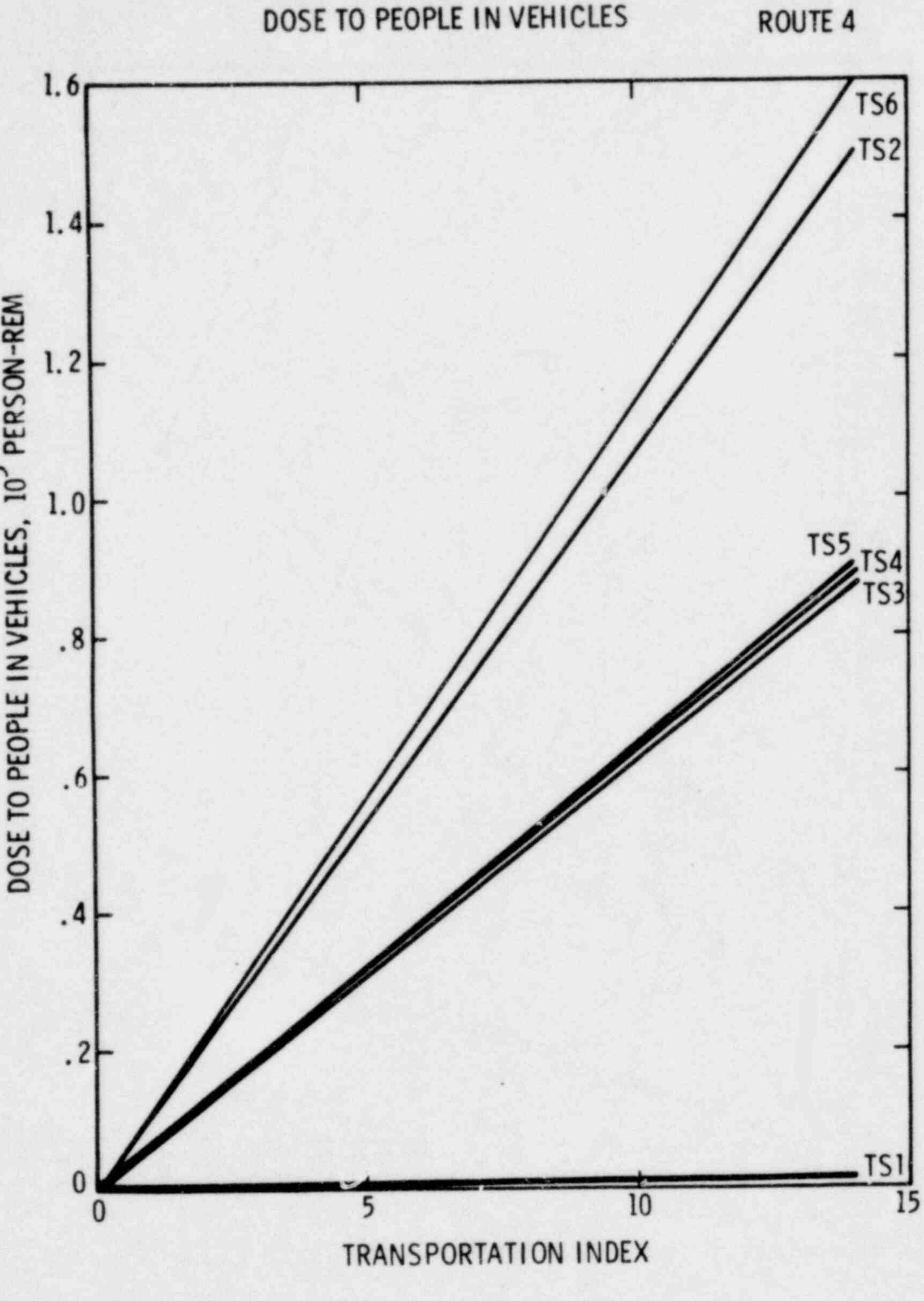


Figure 29. Dose to People in Vehicles vs Transportation Index - Route 4

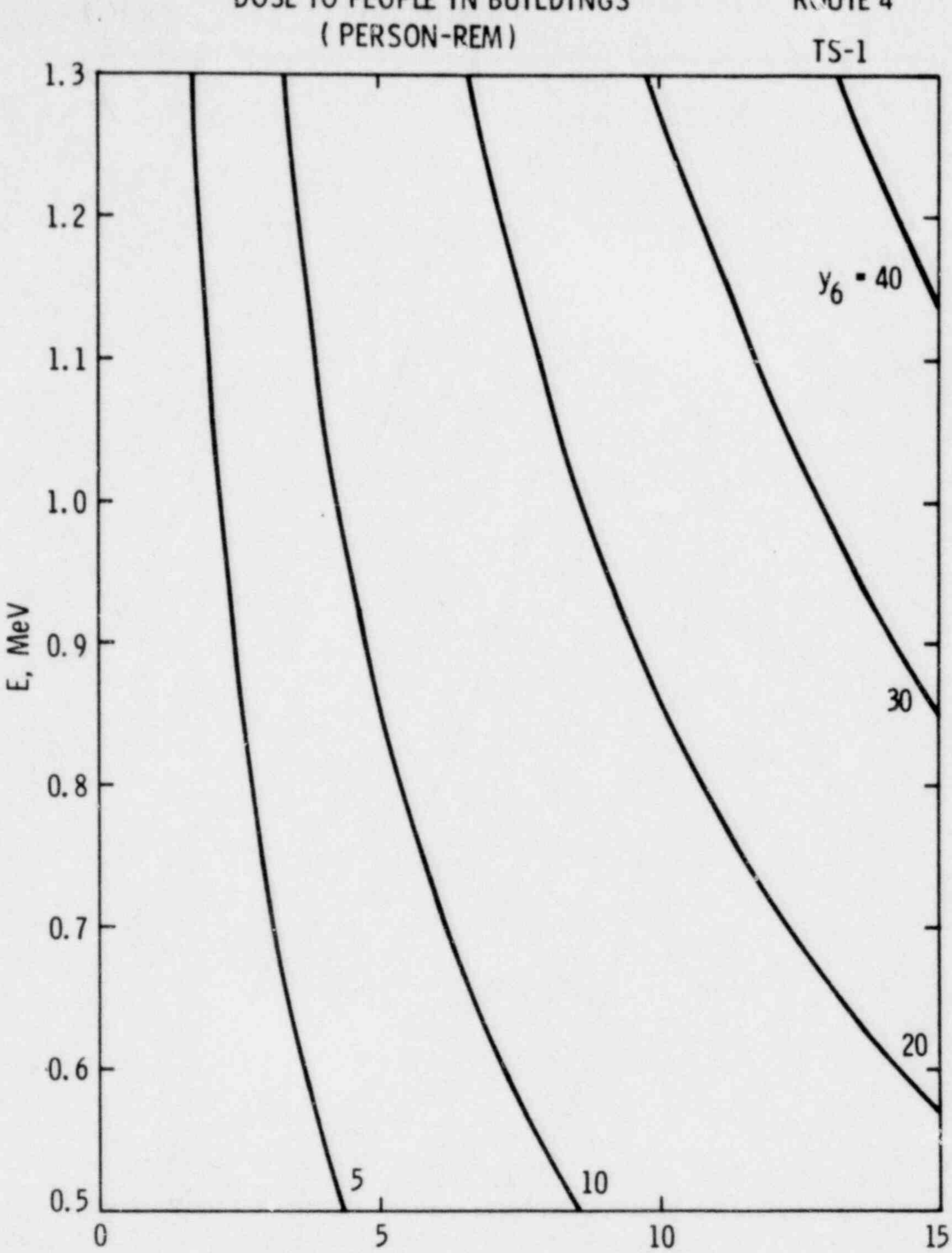


Figure 30. Contours of Constant Dose to People in Buildings - Route 4, TS-1

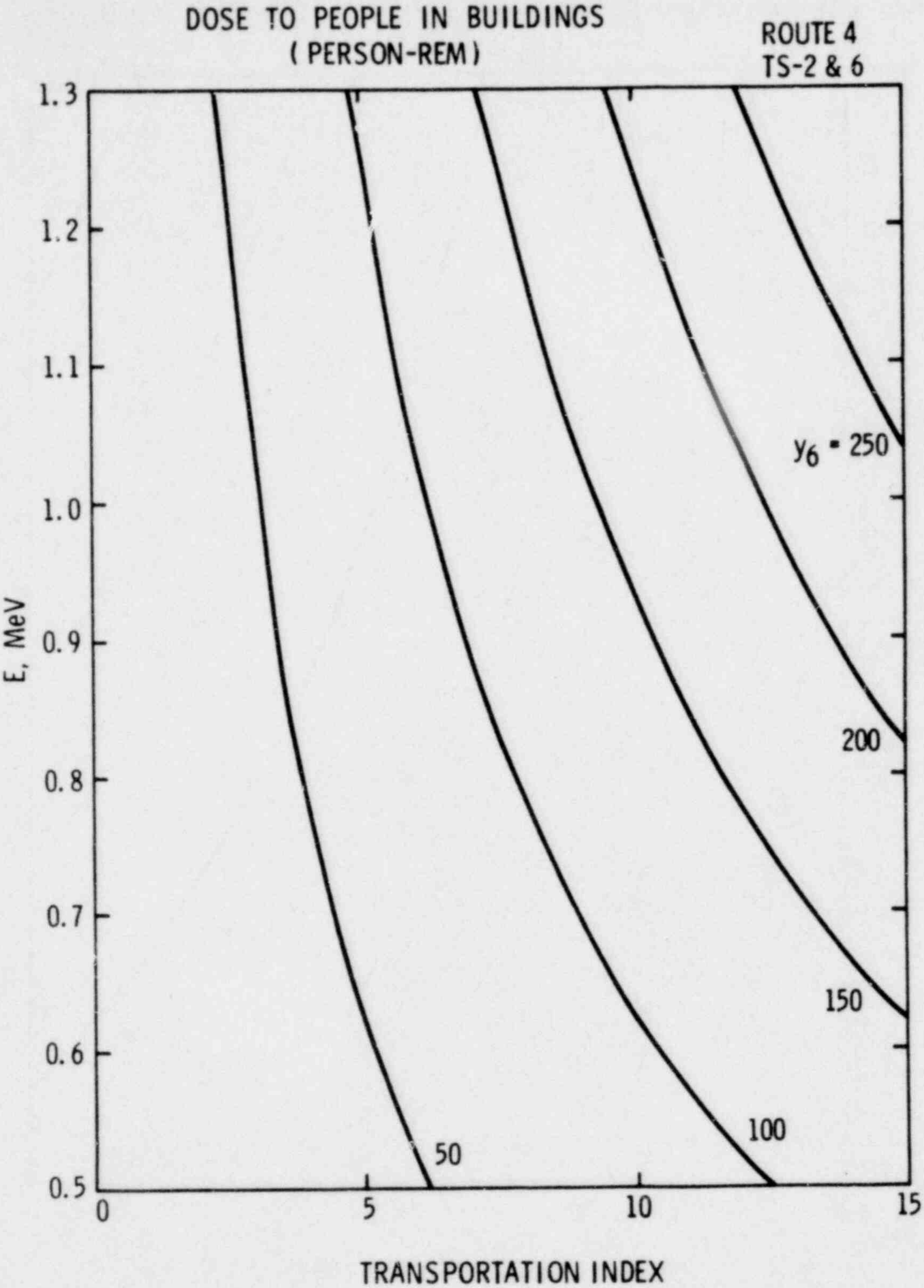


Figure 31. Contours of Constant Dose to People in Buildings - Route 4, TS-2 and 6

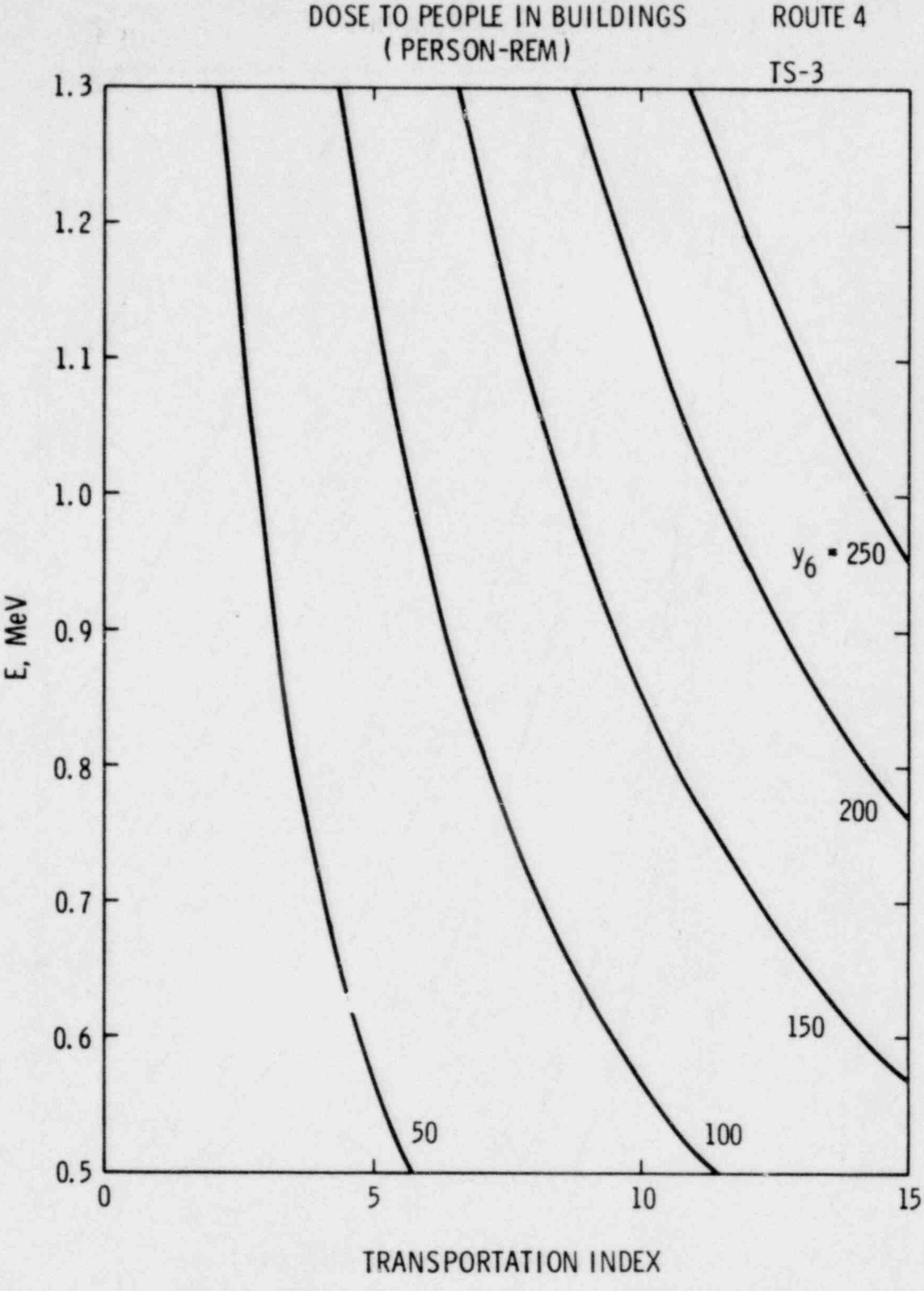


Figure 32. Contours of Constant Dose to People in Buildings - Route 4, TS-3

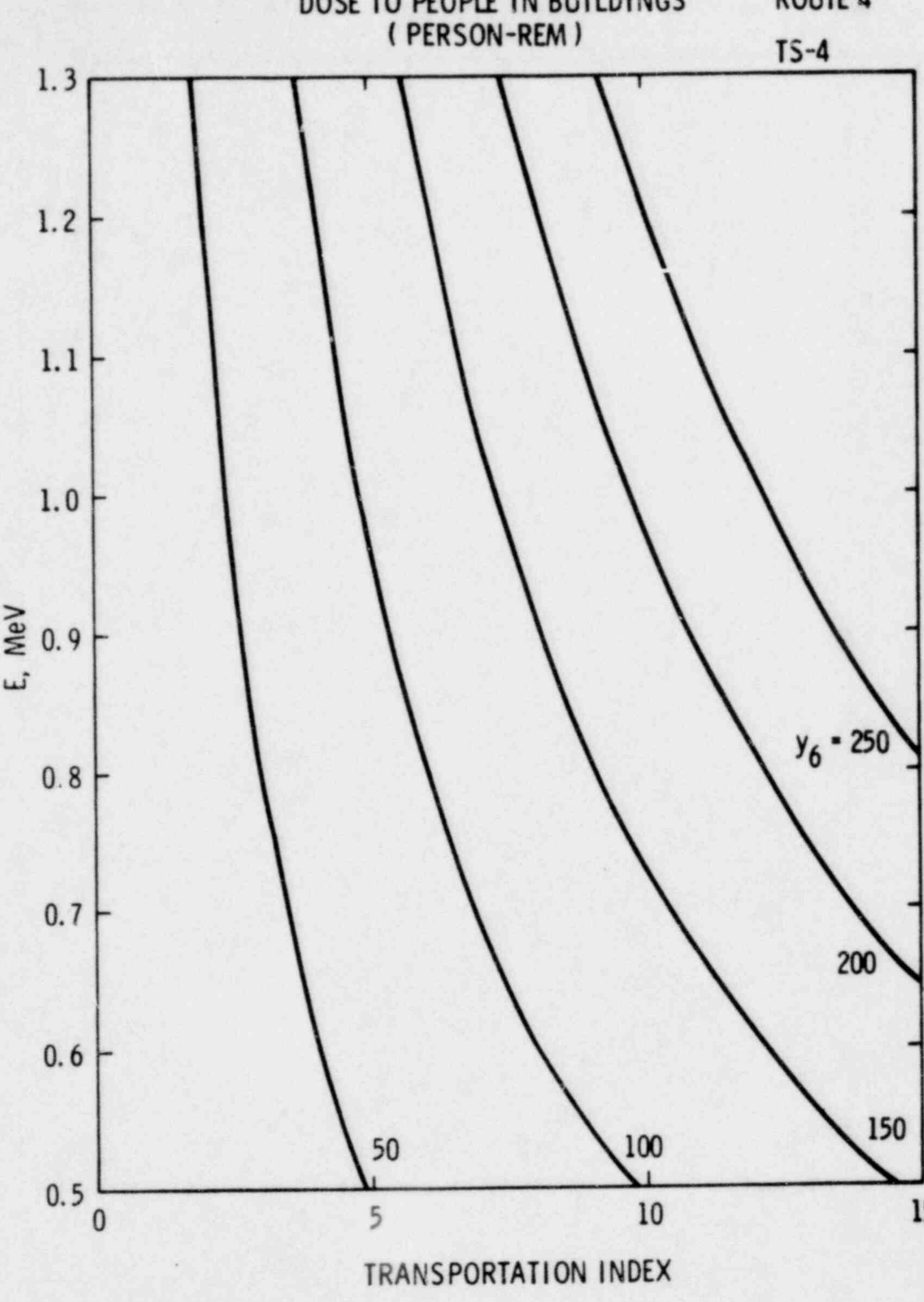


Figure 33. Contours of Constant Dose to People in Buildings - Route 4, TS-4

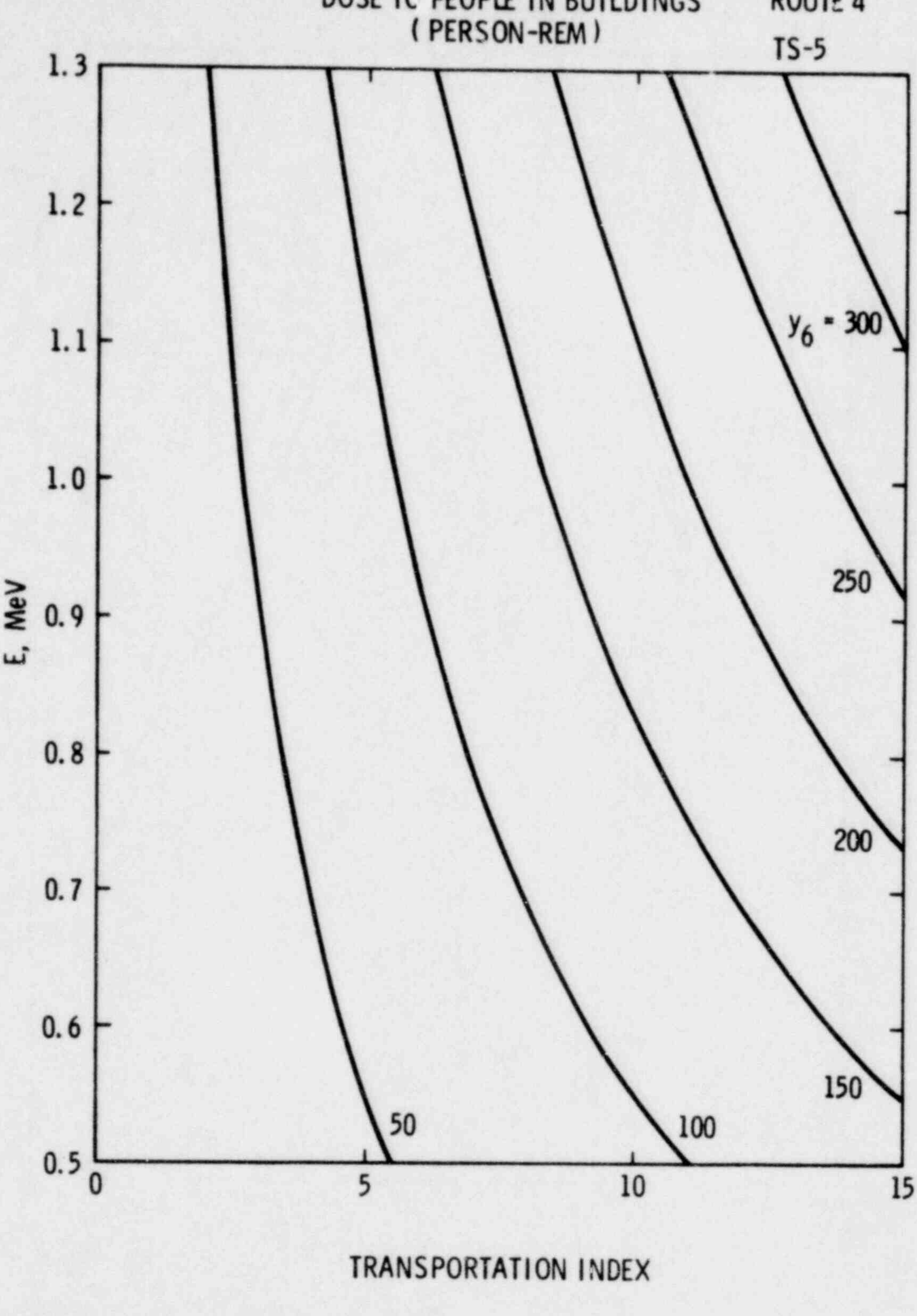


Figure 34. Contours of Constant Dose to People in Buildings - Route 4, TS-5

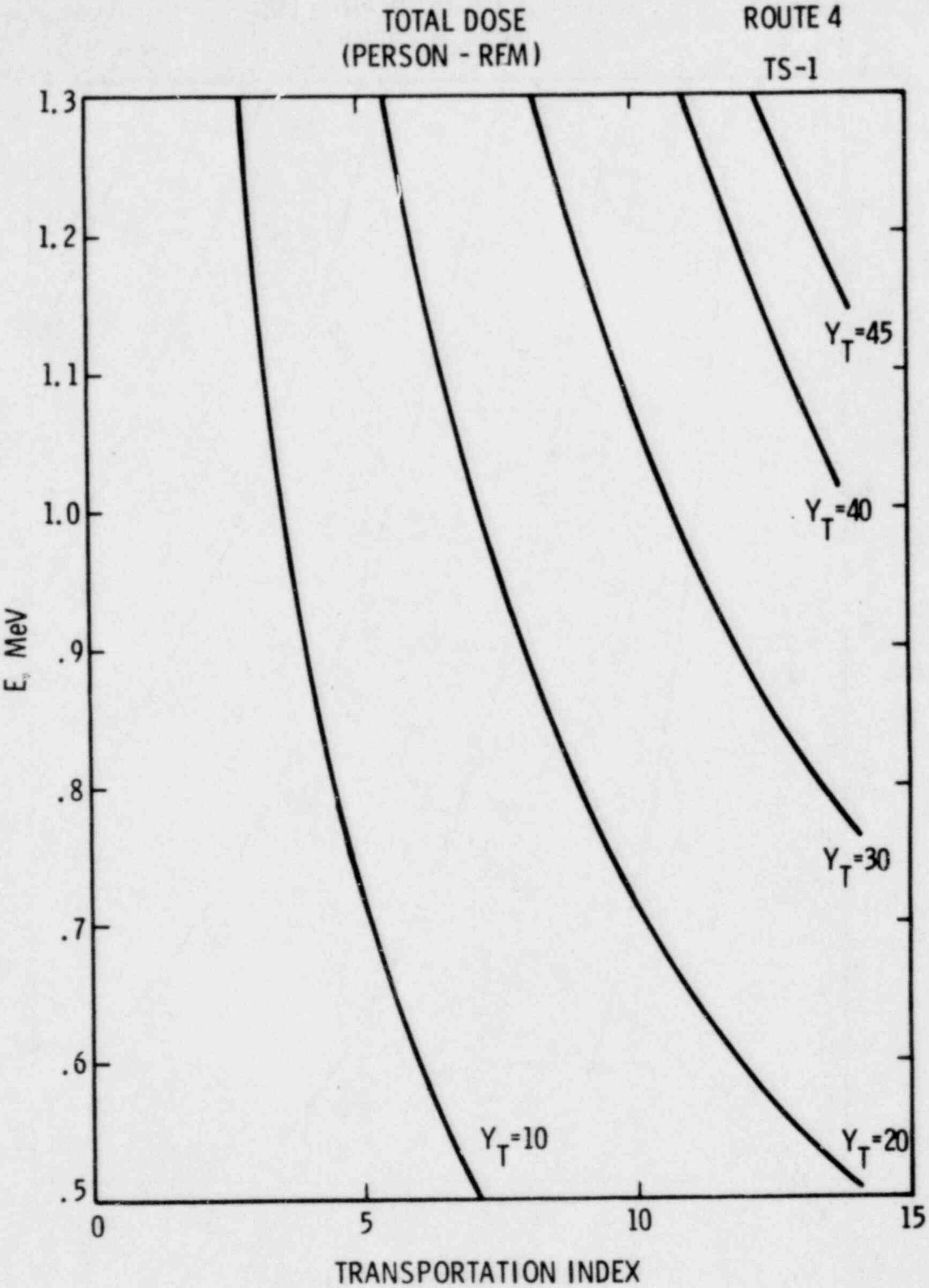


Figure 35. Contours of Constant Total Dose - Route 4, TS-1

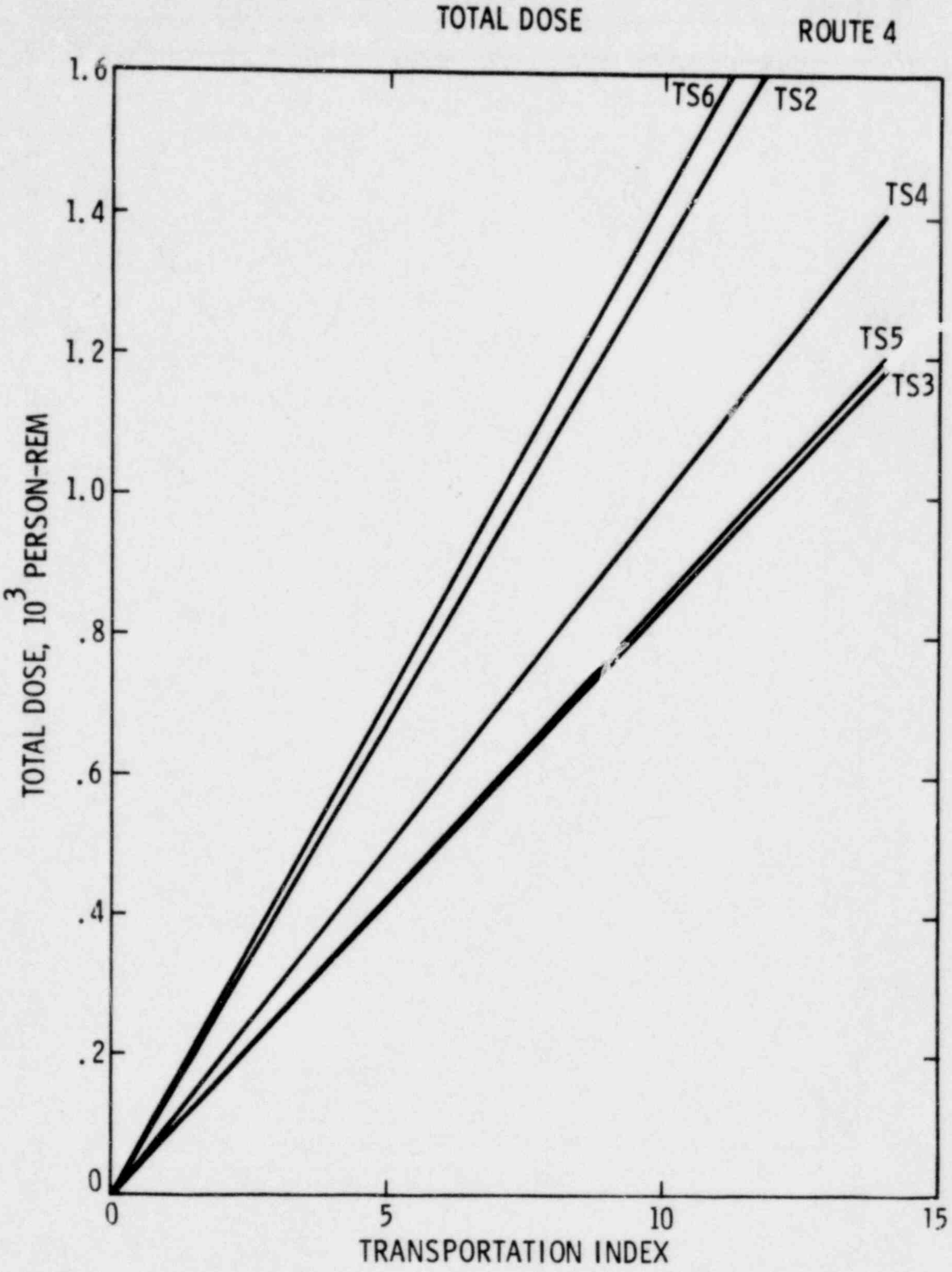


Figure 36. Total Dose vs Transportation Index - Route 4

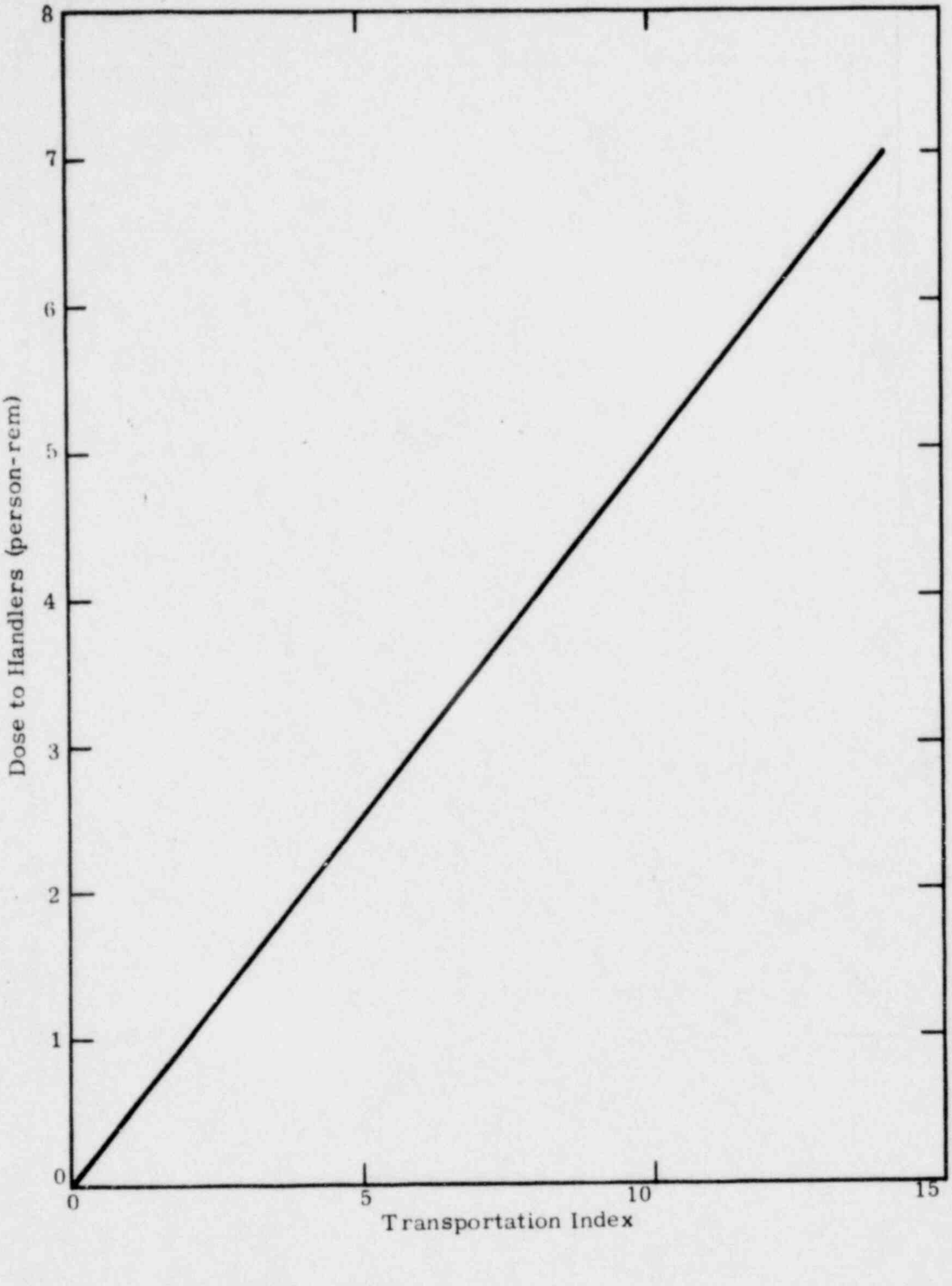


Figure 37. Dose to Hai ers vs Transportation Index

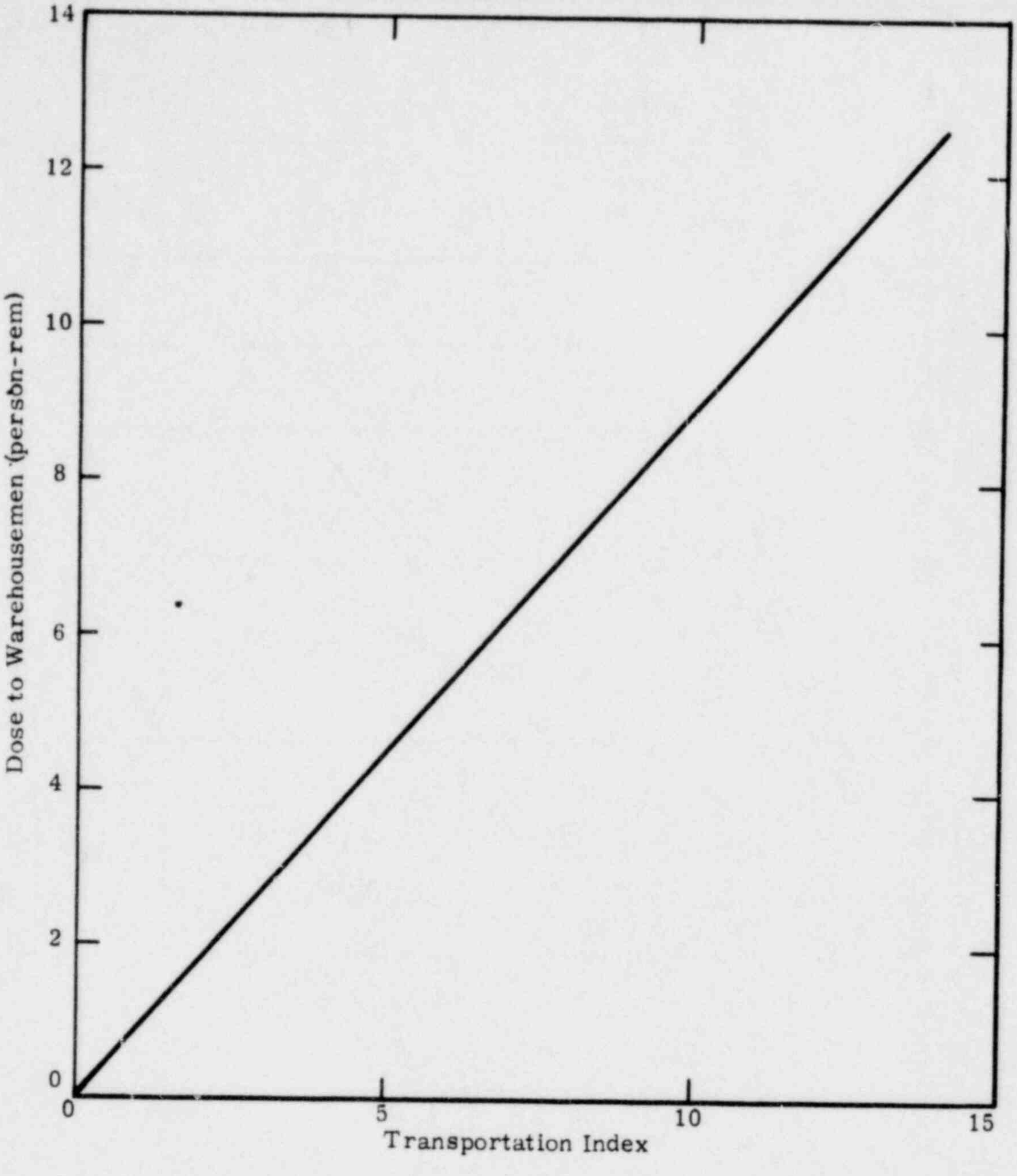


Figure 38. Dose to Warehousemen vs Transportation Index

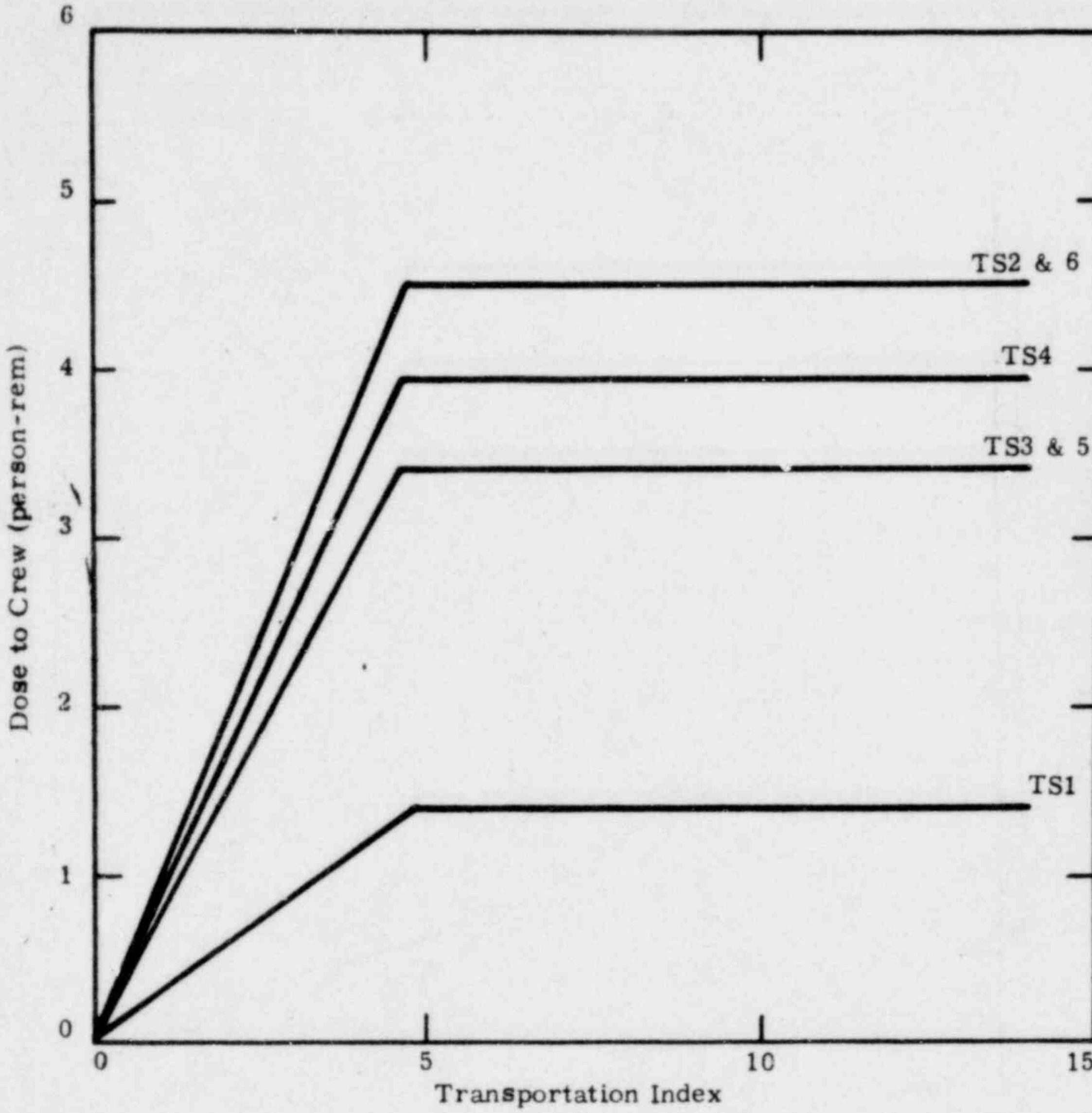


Figure 39. Dose to Crew vs Transportation Index

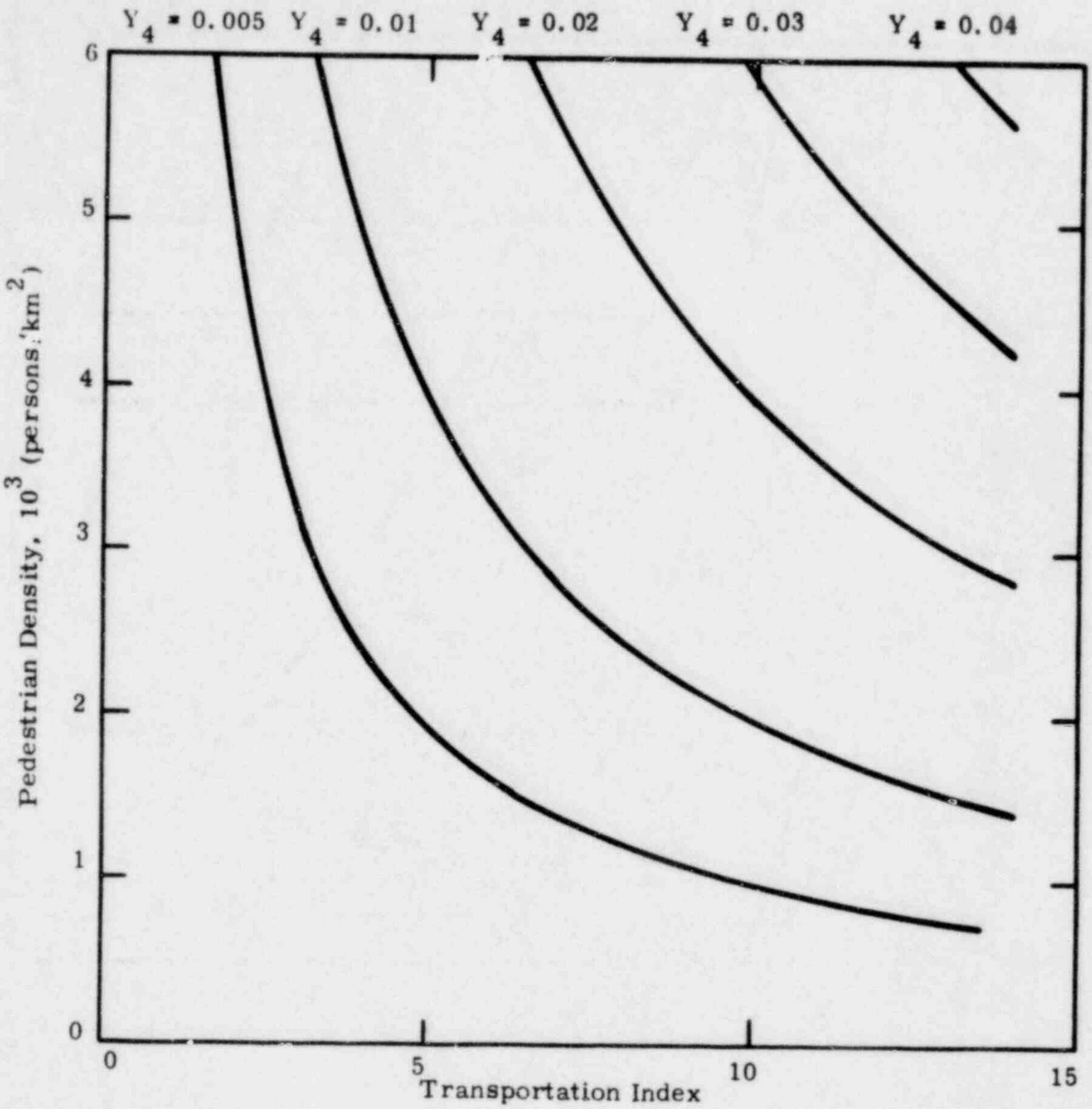


Figure 40. Contour of Constant Dose to Pedestrians - TS-1

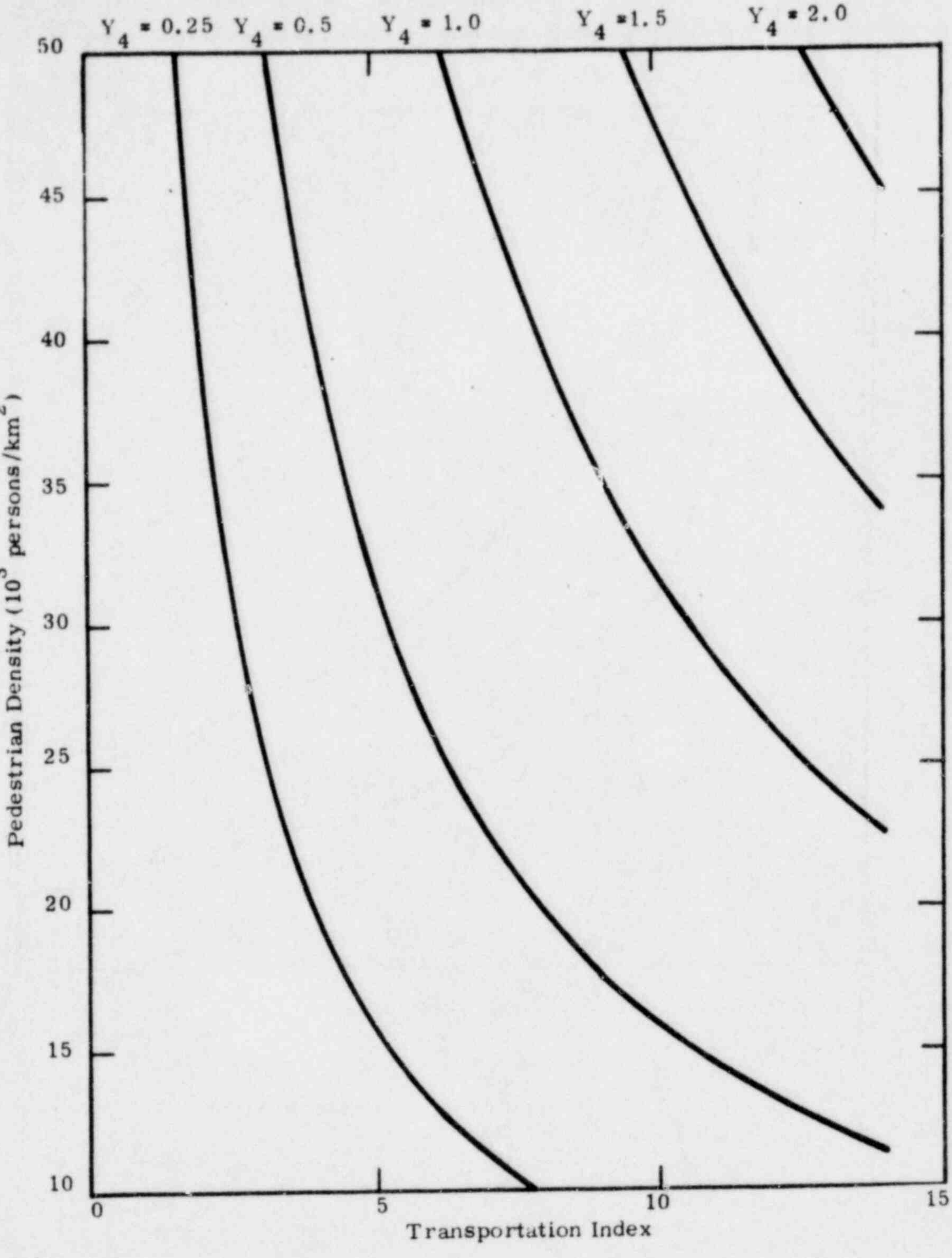


Figure 41. Contours of Constant Dose to Pedestrians - TS-2 and 6

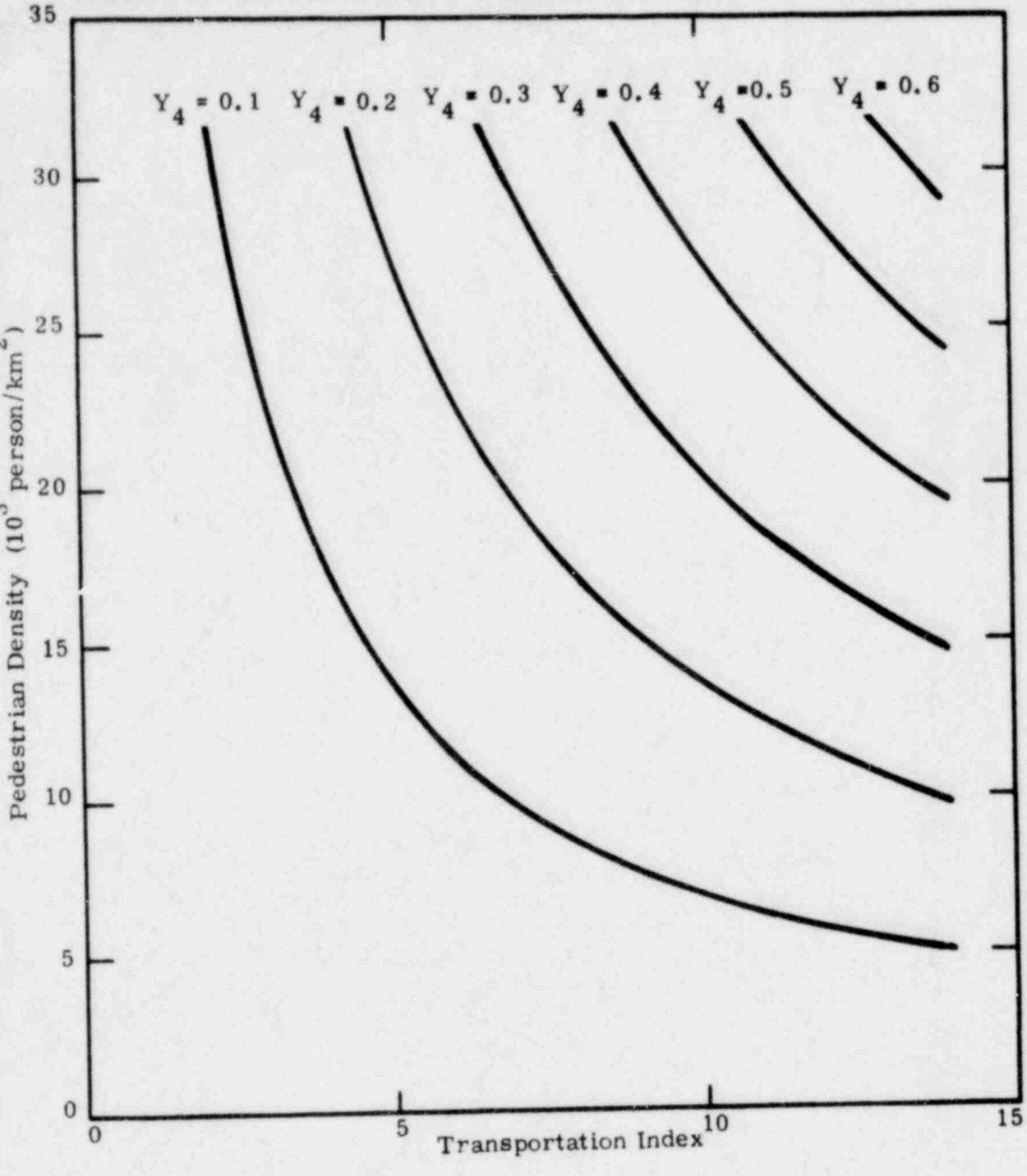


Figure 42. Contours of Constant Dose to Pedestrians - TS-3 and 5

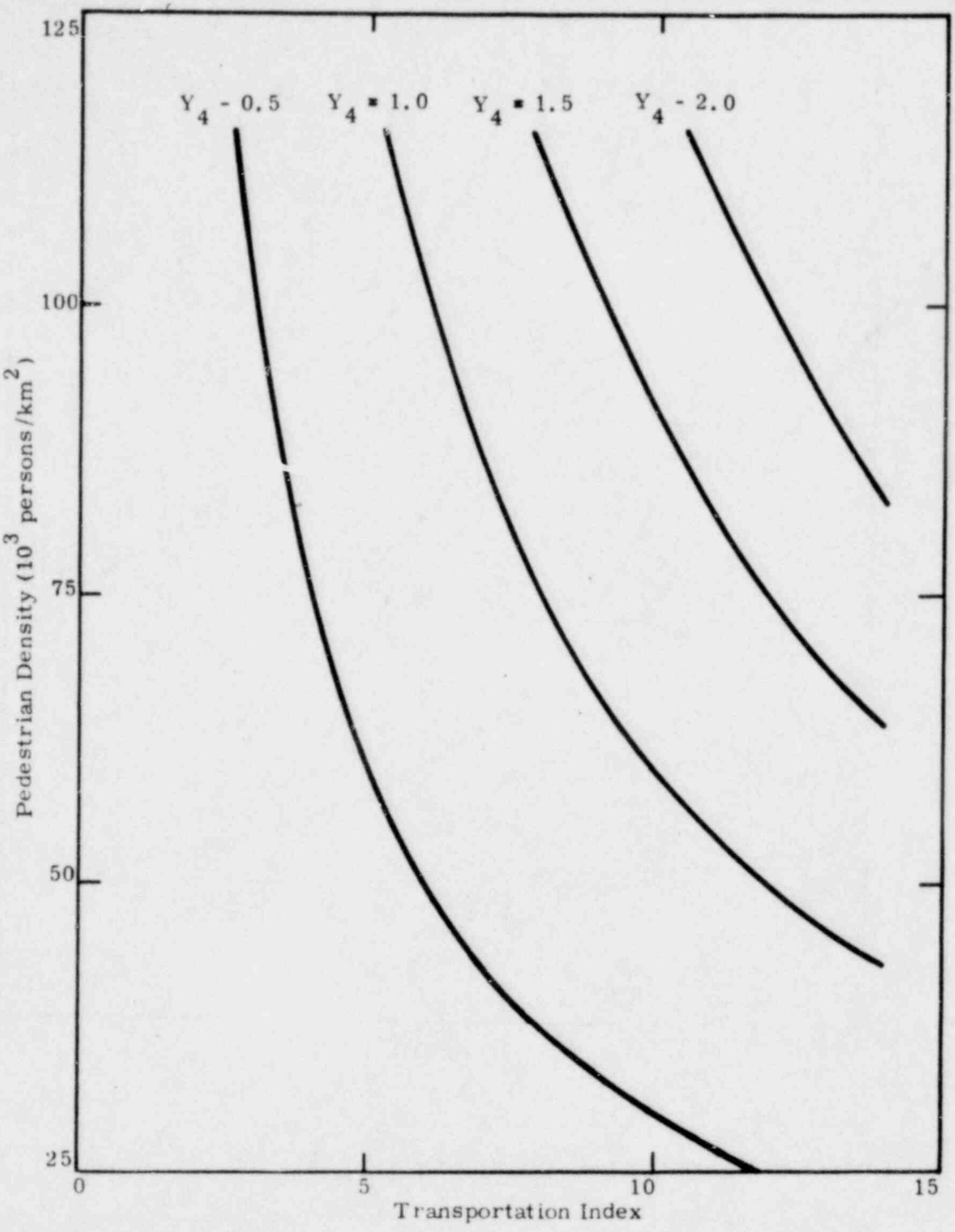


Figure 43. Contours of Constant Dose to Pedestrians - TS-4

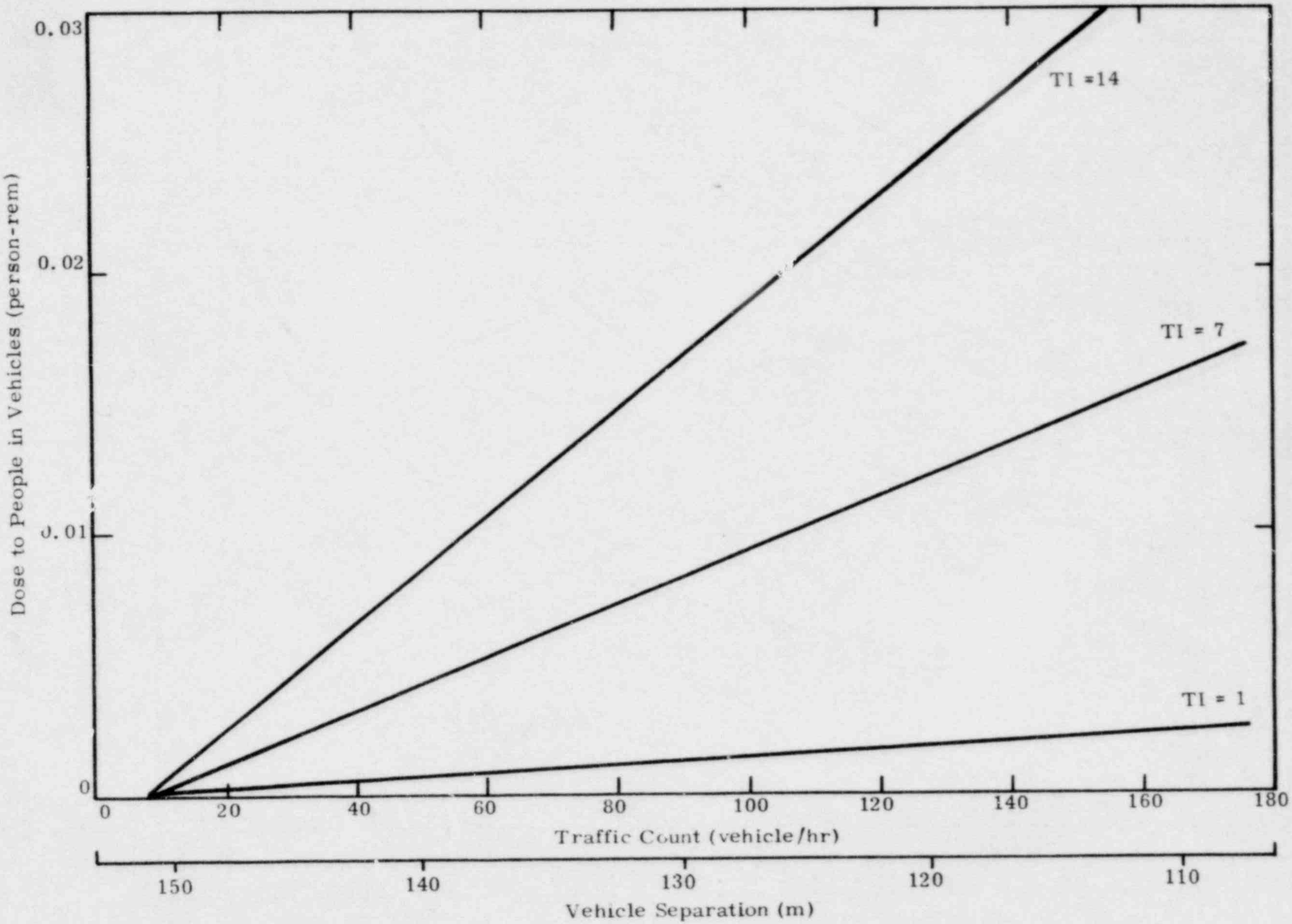


Figure 44. Dose to People in Vehicles vs Traffic Count/Vehicles Separation Distance - TS-1

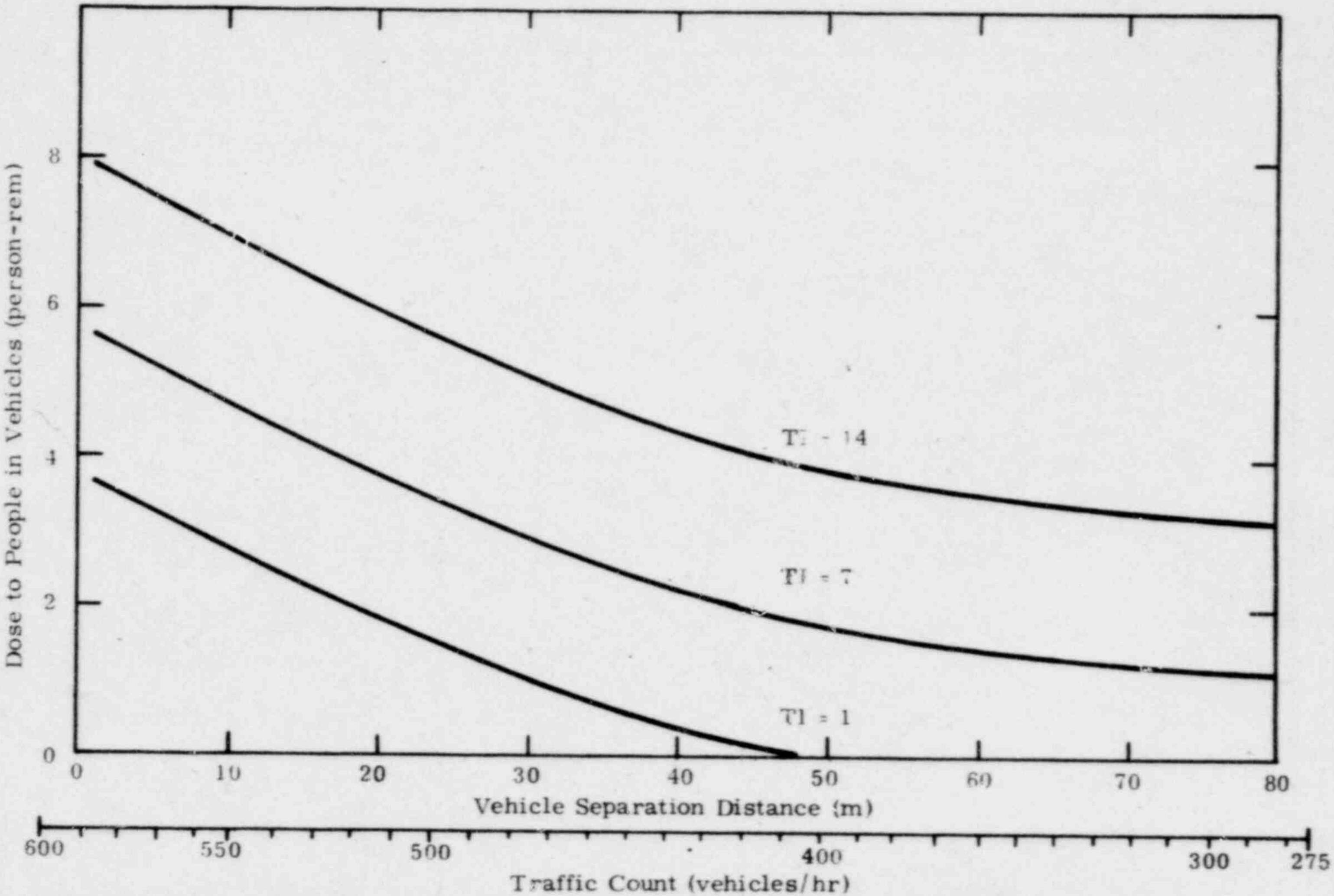


Figure 45. Dose to People in Vehicles vs Traffic Count/Vehicle Separation Distance - TS-2 and 6

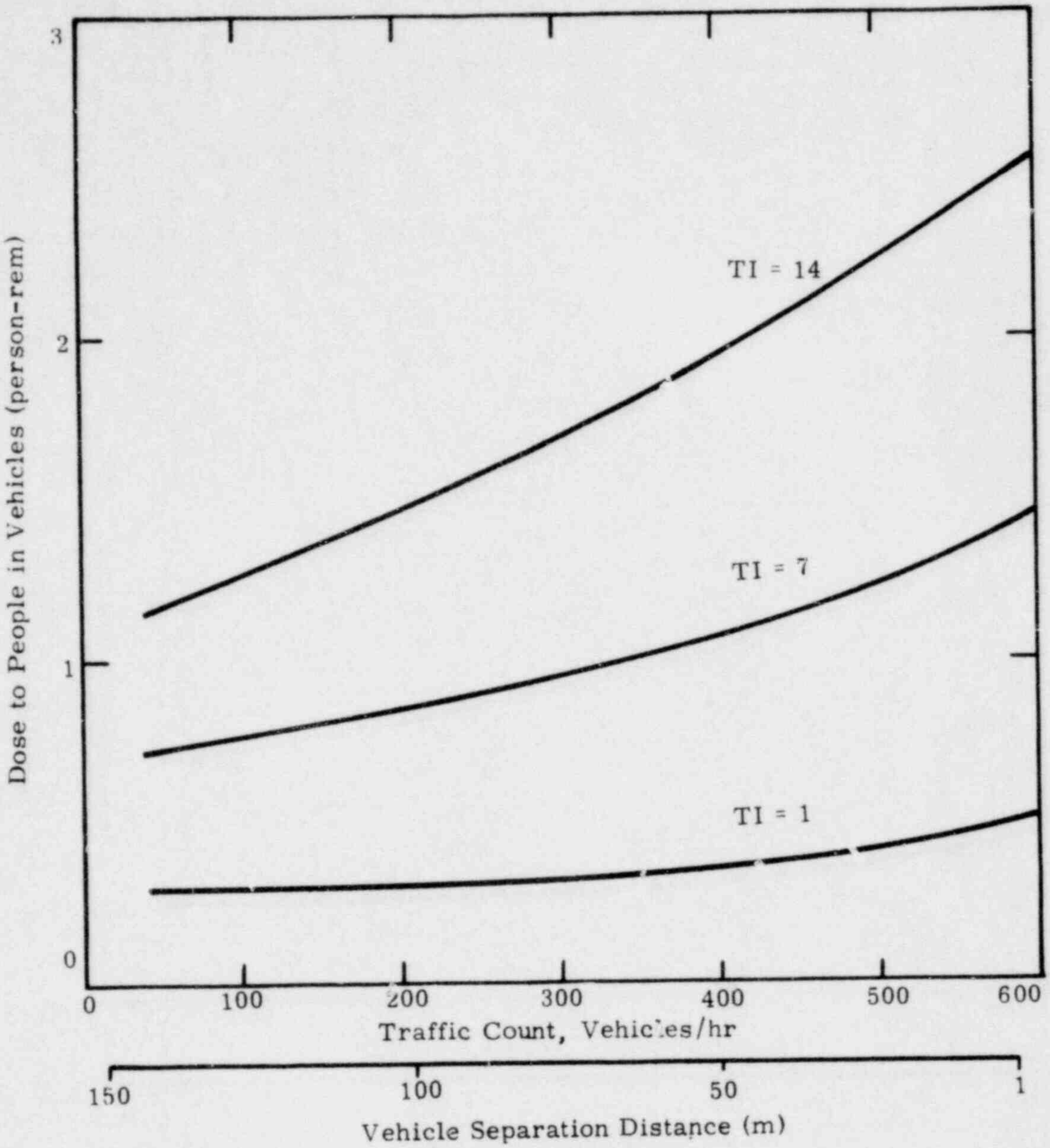


Figure 46. Dose to People in Vehicles vs Traffic Count/Vehicle Separation Distance - TS-3 and 5

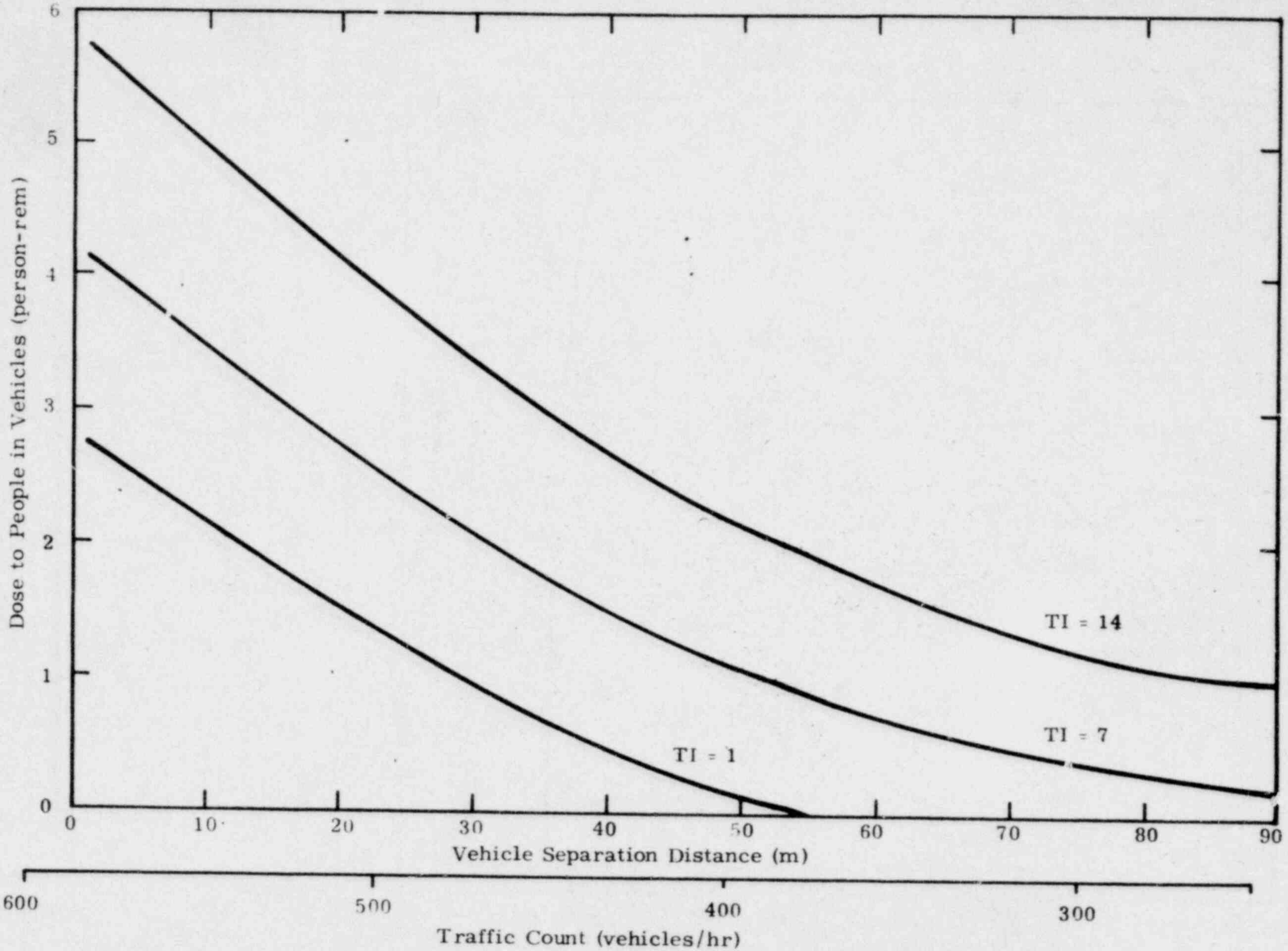


Figure 47. Dose to People in Vehicles vs Traffic Count/Vehicle Separation Distance - TS-4

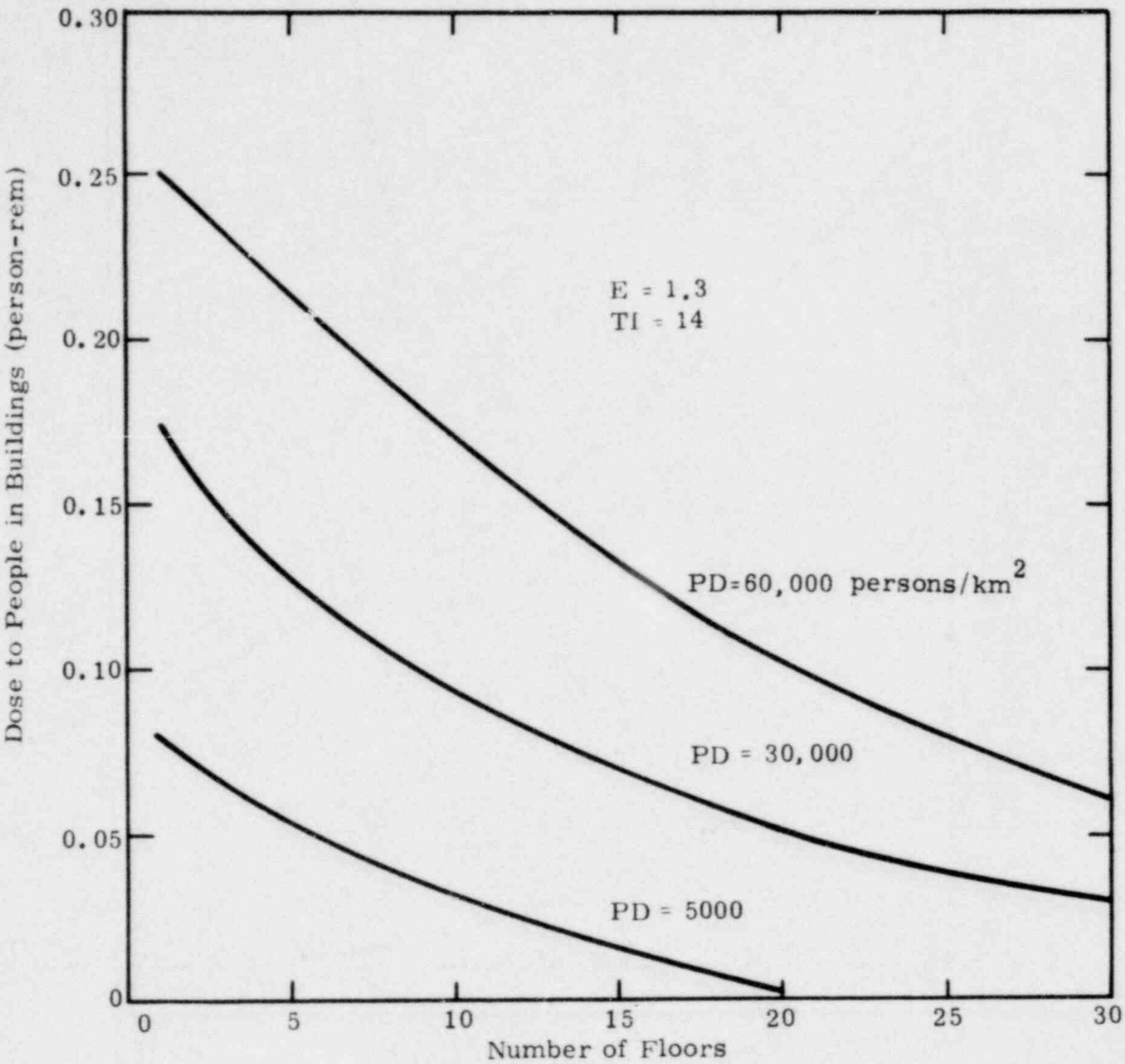


Figure 48. Dose to People in Buildings vs Number of Floors - Showing Effect of Population Density - TS-1

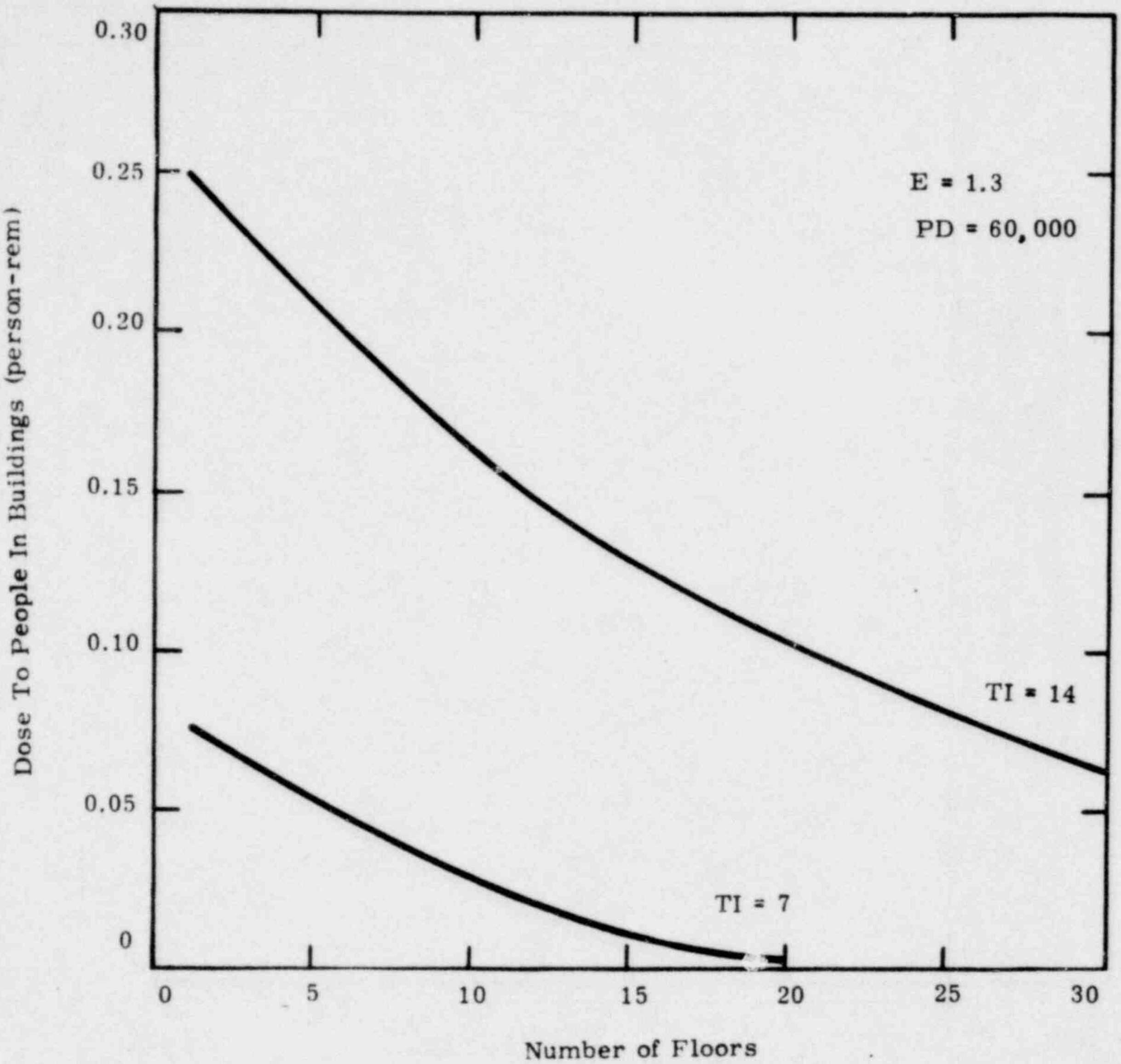


Figure 49. Dose to People in Buildings vs Number of Floors - showing effect of TI - TS-1

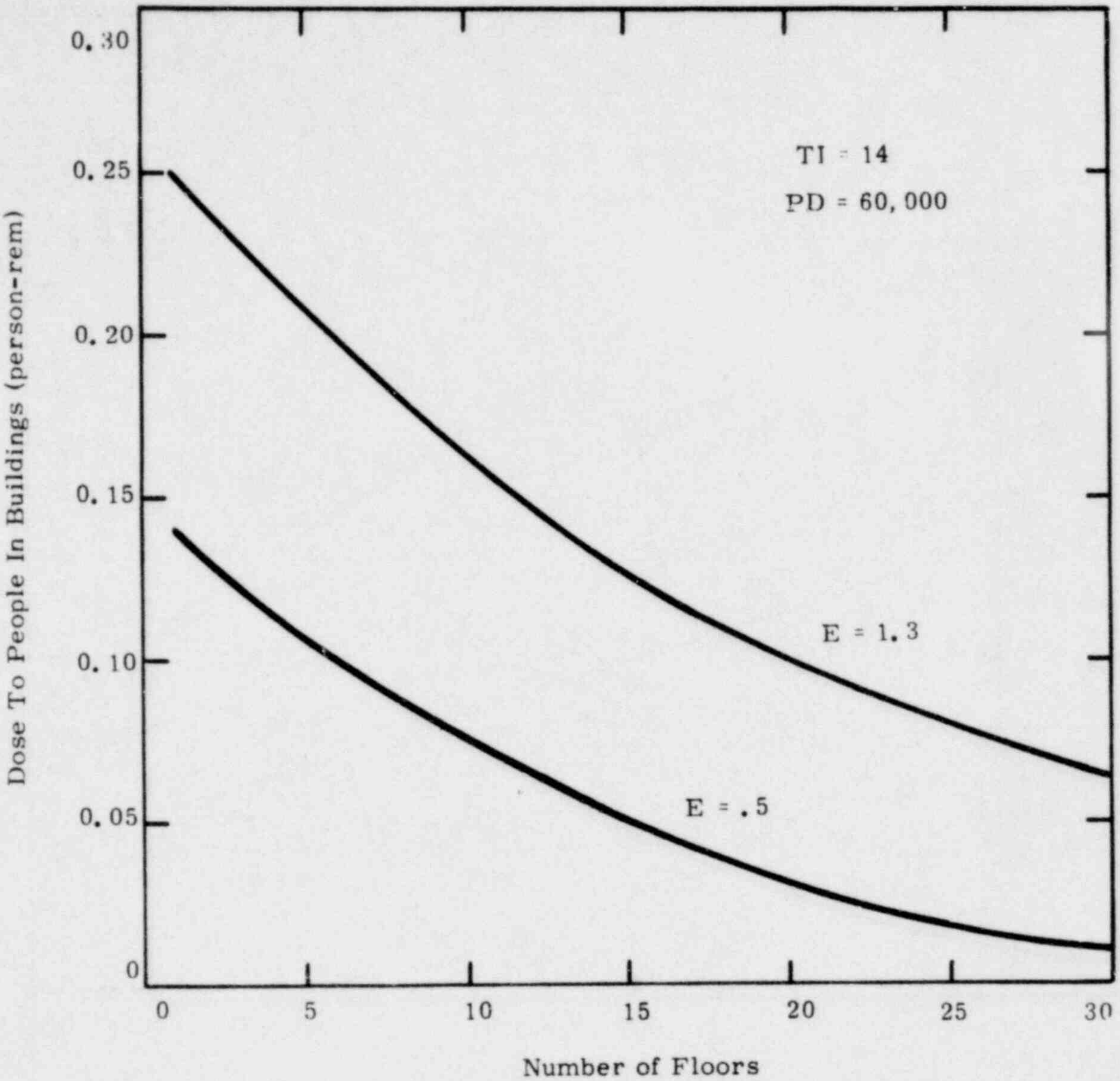


Figure 50. Dose to People in Buildings vs Number of Floors - Showing the Effect of E - TS-1

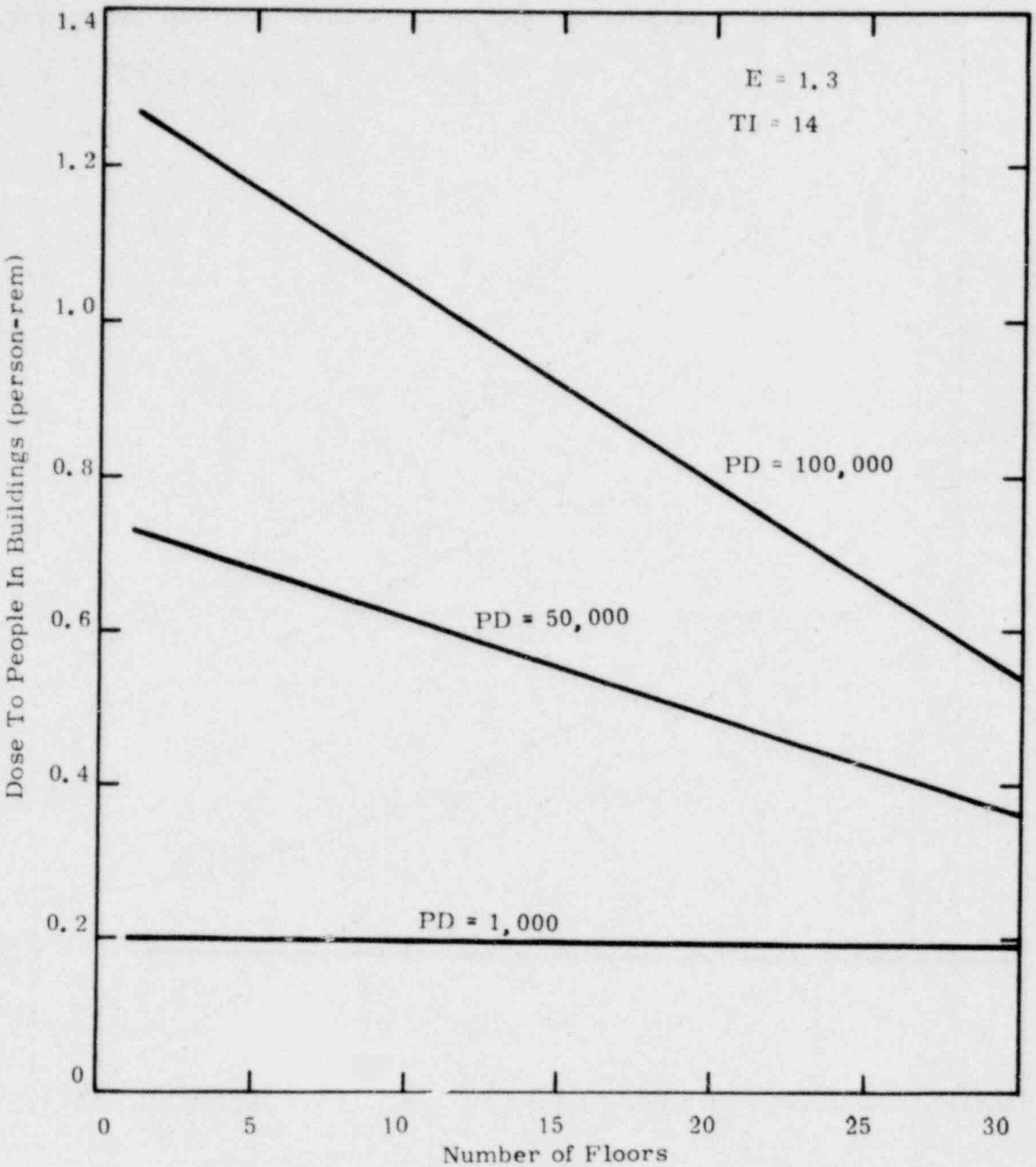


Figure 51. Dose to People in Buildings vs Number of Floors - Showing Effect of PD - TS-2 and 6

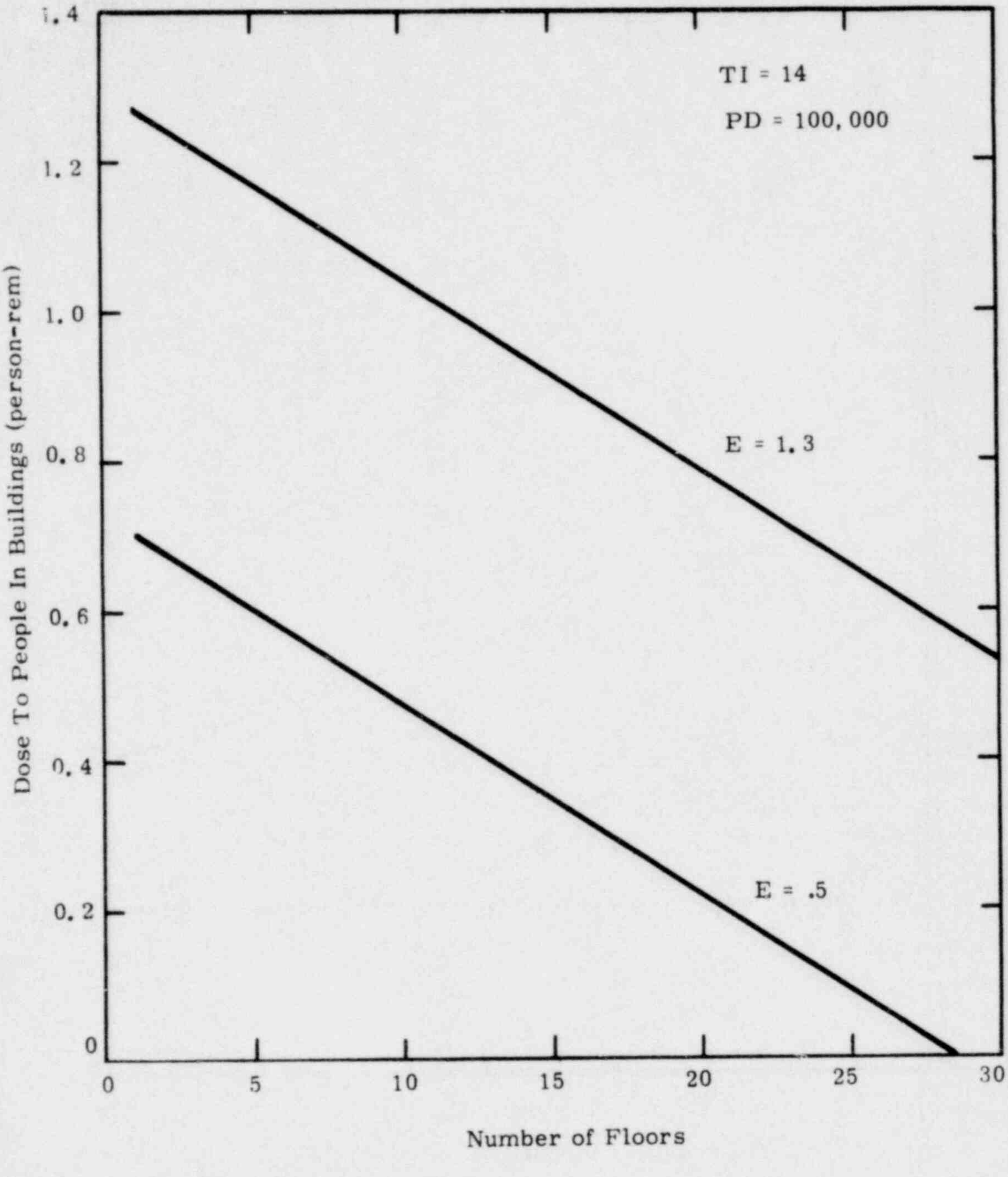


Figure 52. Dose to People in Buildings vs Number of Floors - Showing Effect of E - TS-2 and 6

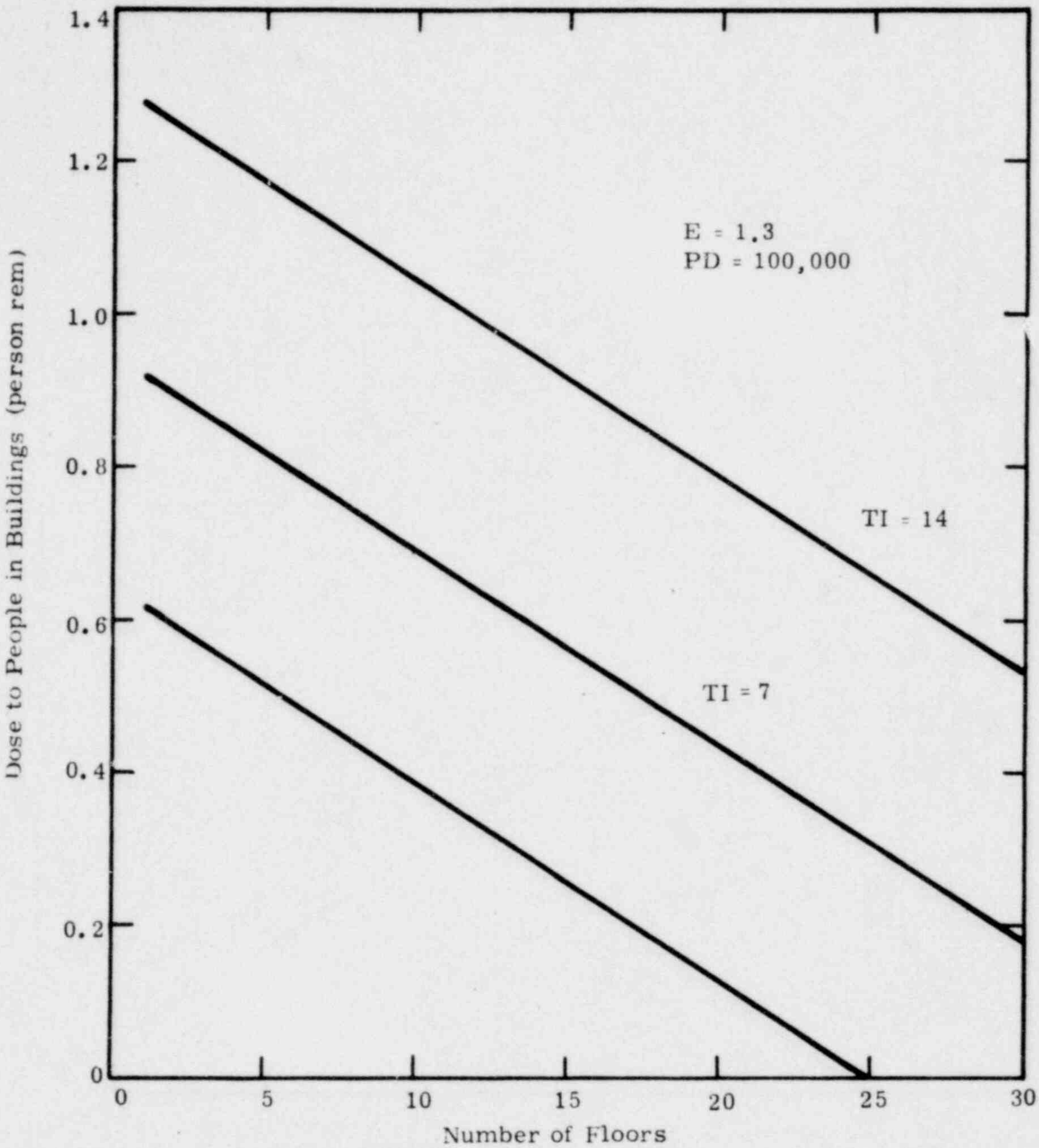


Figure 53. Dose to People in Buildings vs Number of Floors - Showing Effect of TI - TS-2 and 6

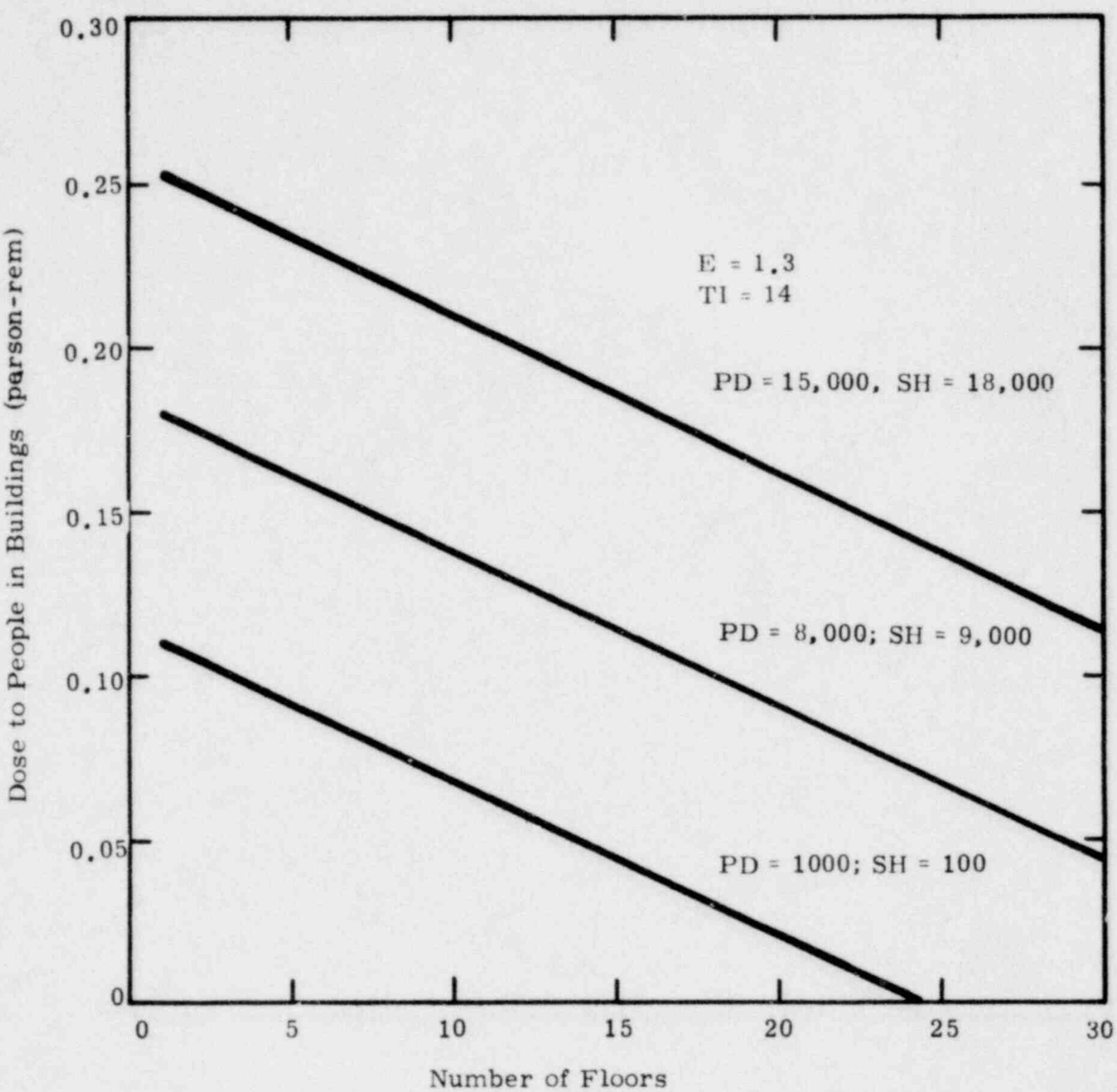


Figure 54. Dose to People in Buildings vs Number of Floors - Showing Effect of PD and SHOPED - TS-3 and 5

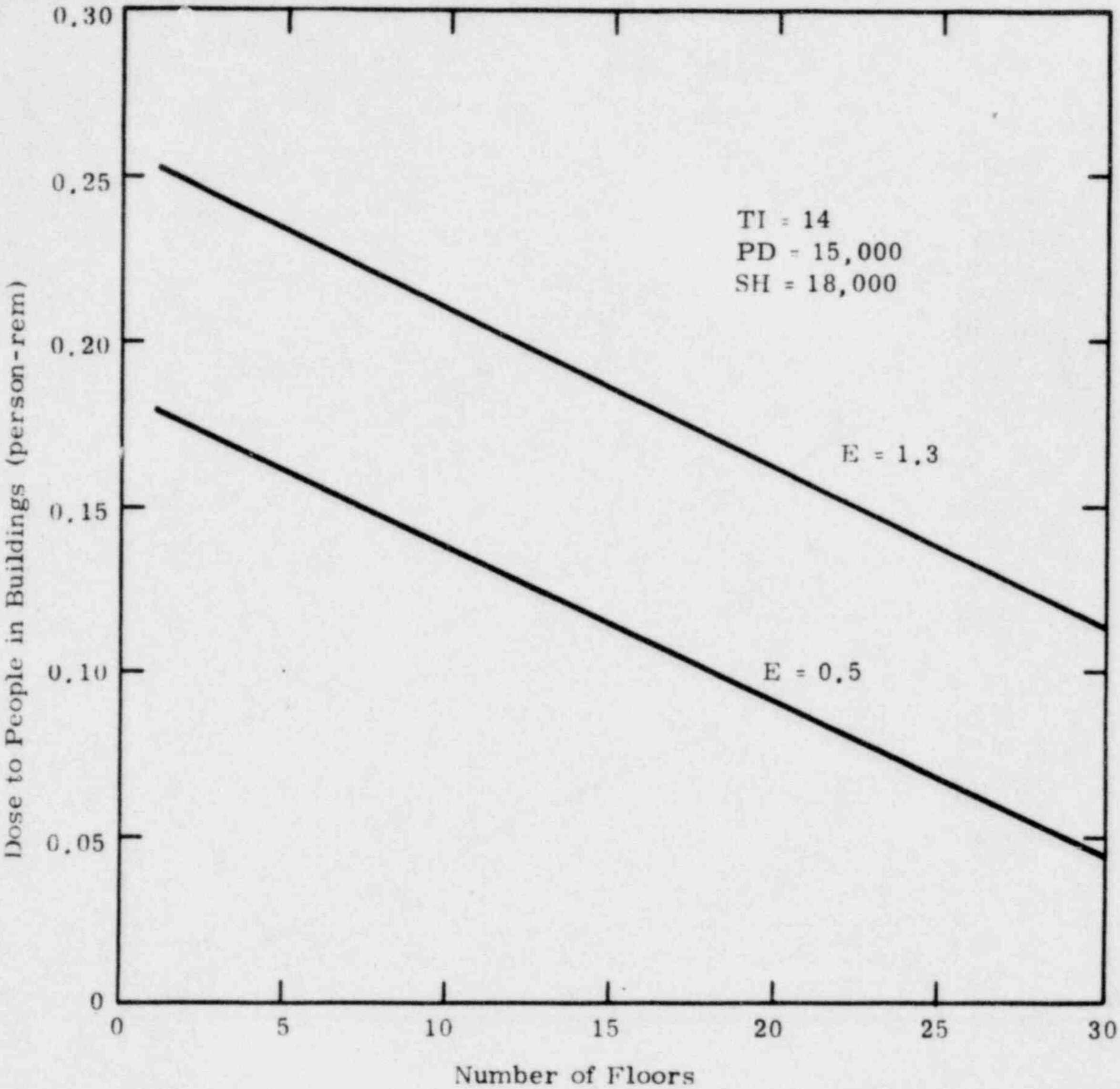


Figure 55. Dose to People in Buildings vs Number of Floors - Showing Effect of E - TS-3 and 5

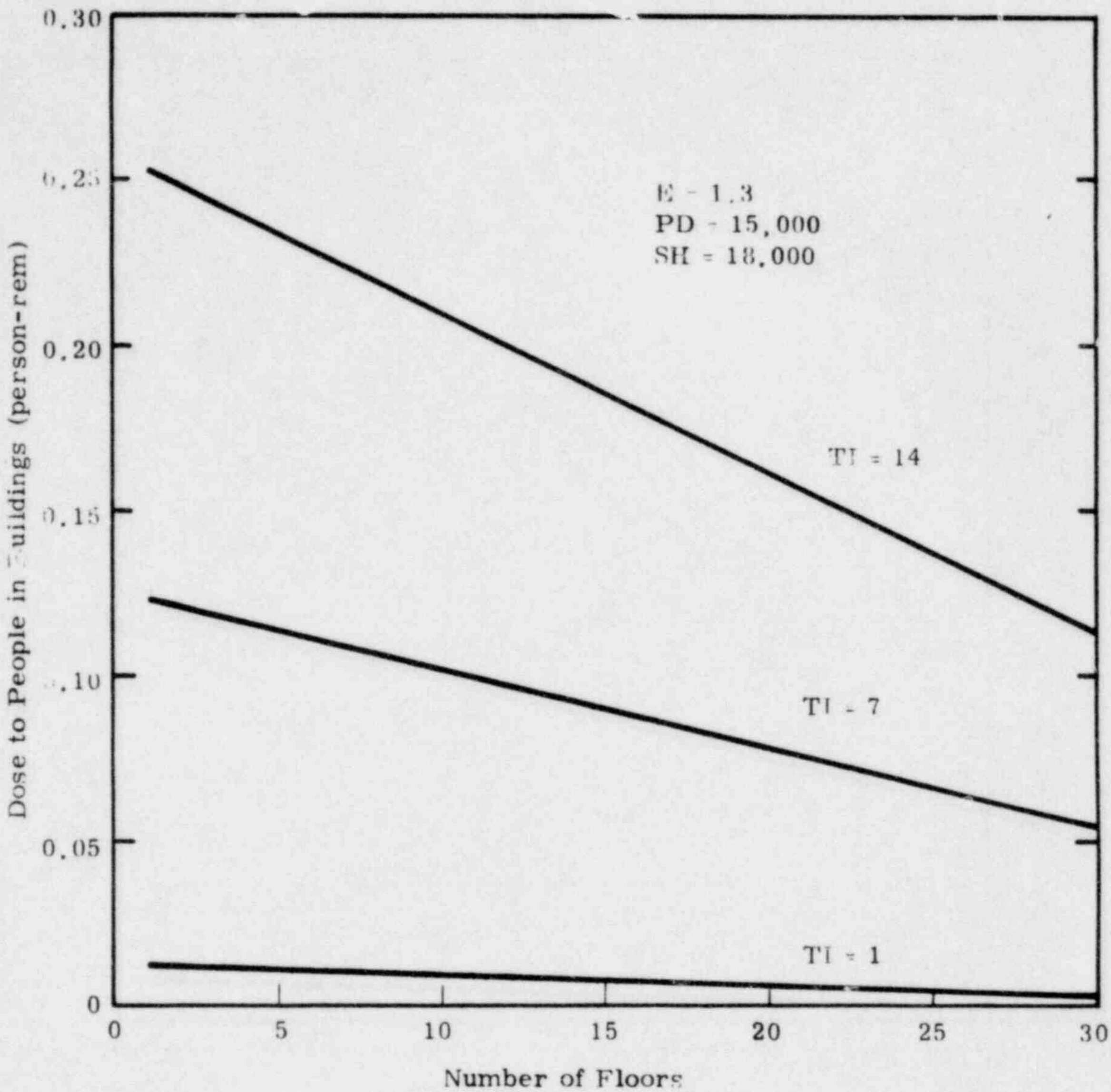


Figure 56. Dose to People in Buildings vs Number of Floors - Showing Effect of TI - TS-3 and 5

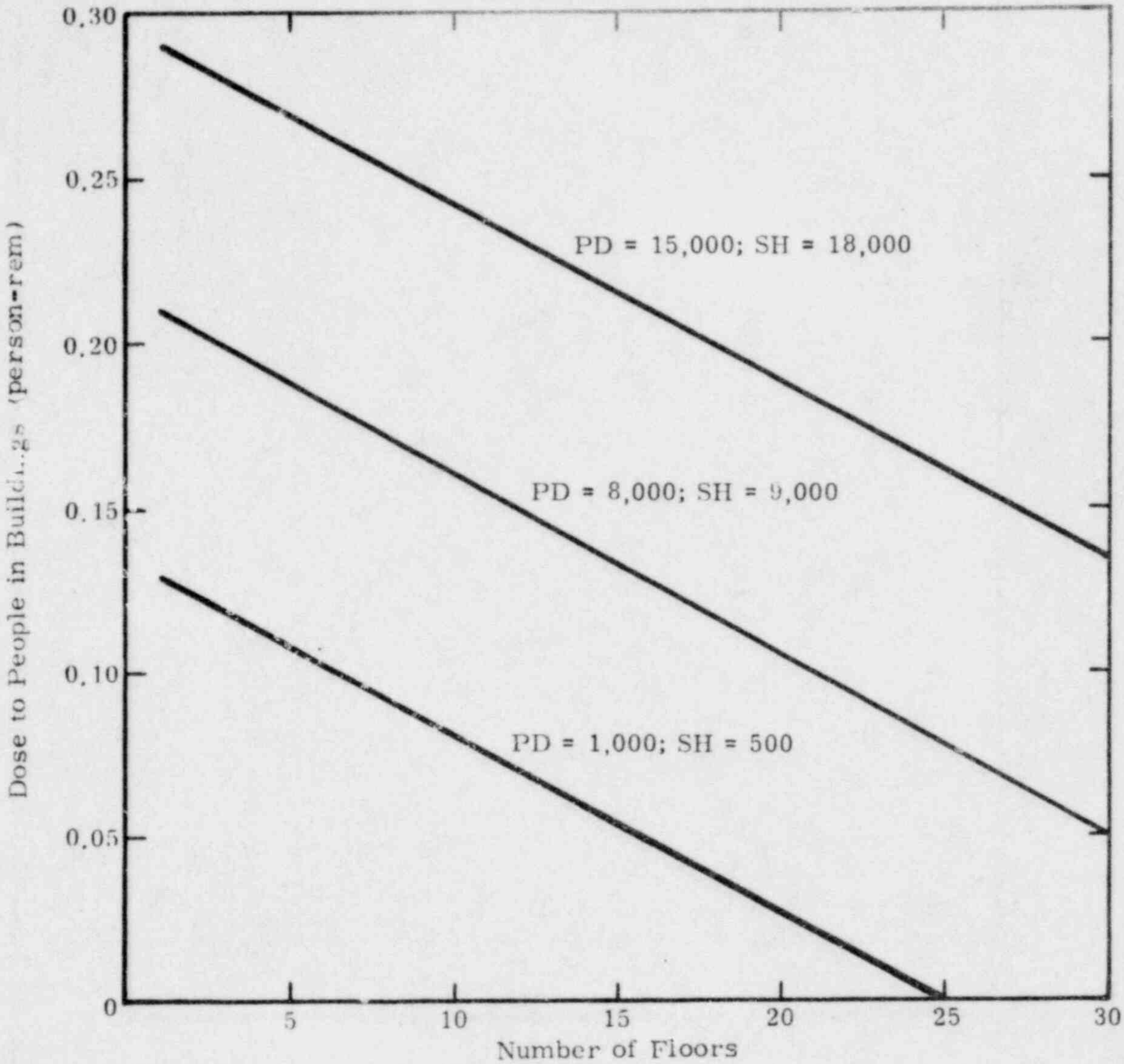


Figure 57. Dose to People in Buildings vs Number of Floors - Showing Effect of PD and SHOPED - TS-4

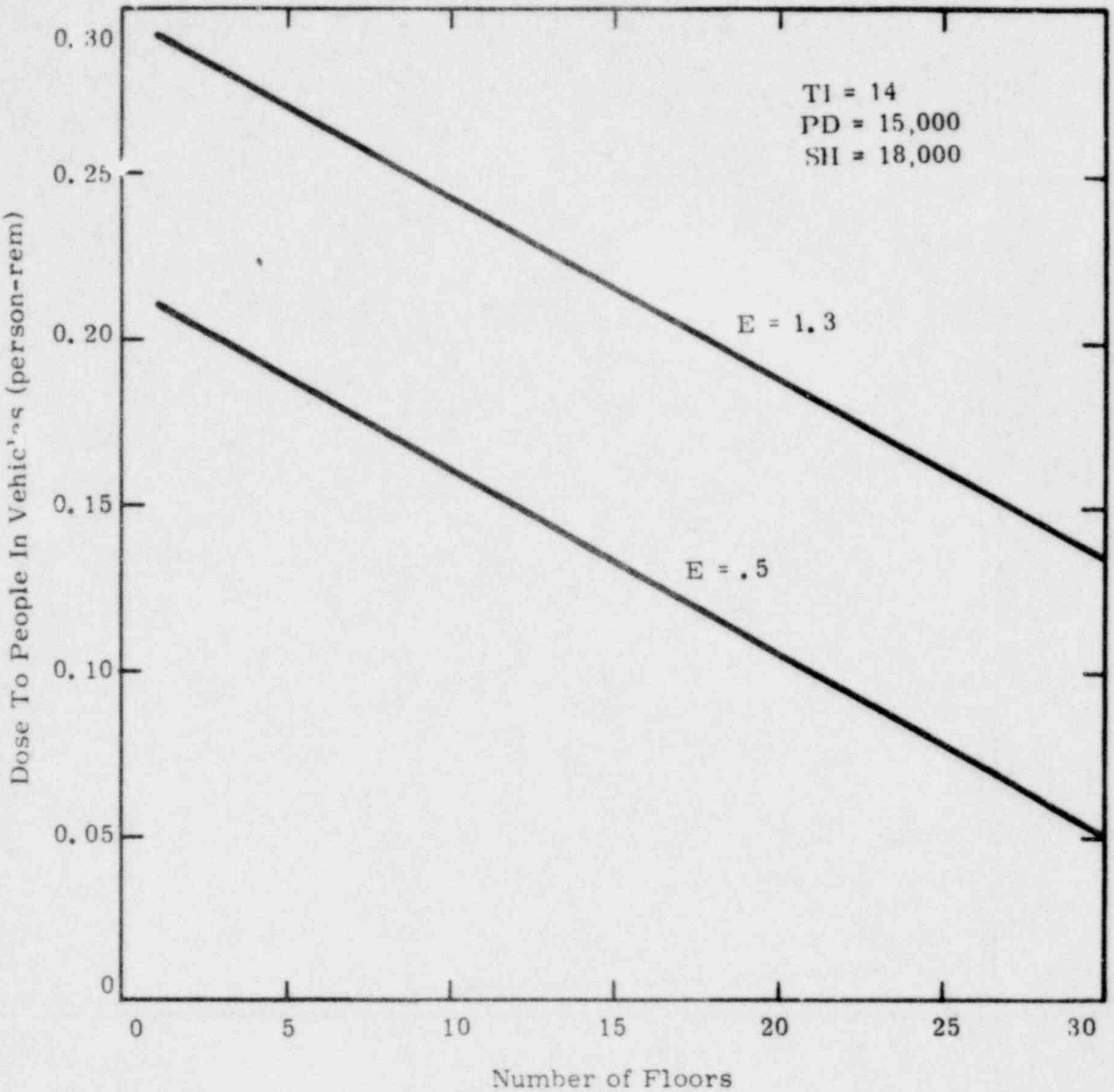


Figure 58. Dose to People in Buildings vs Number of Floors - Showing Effect of E - TS-4

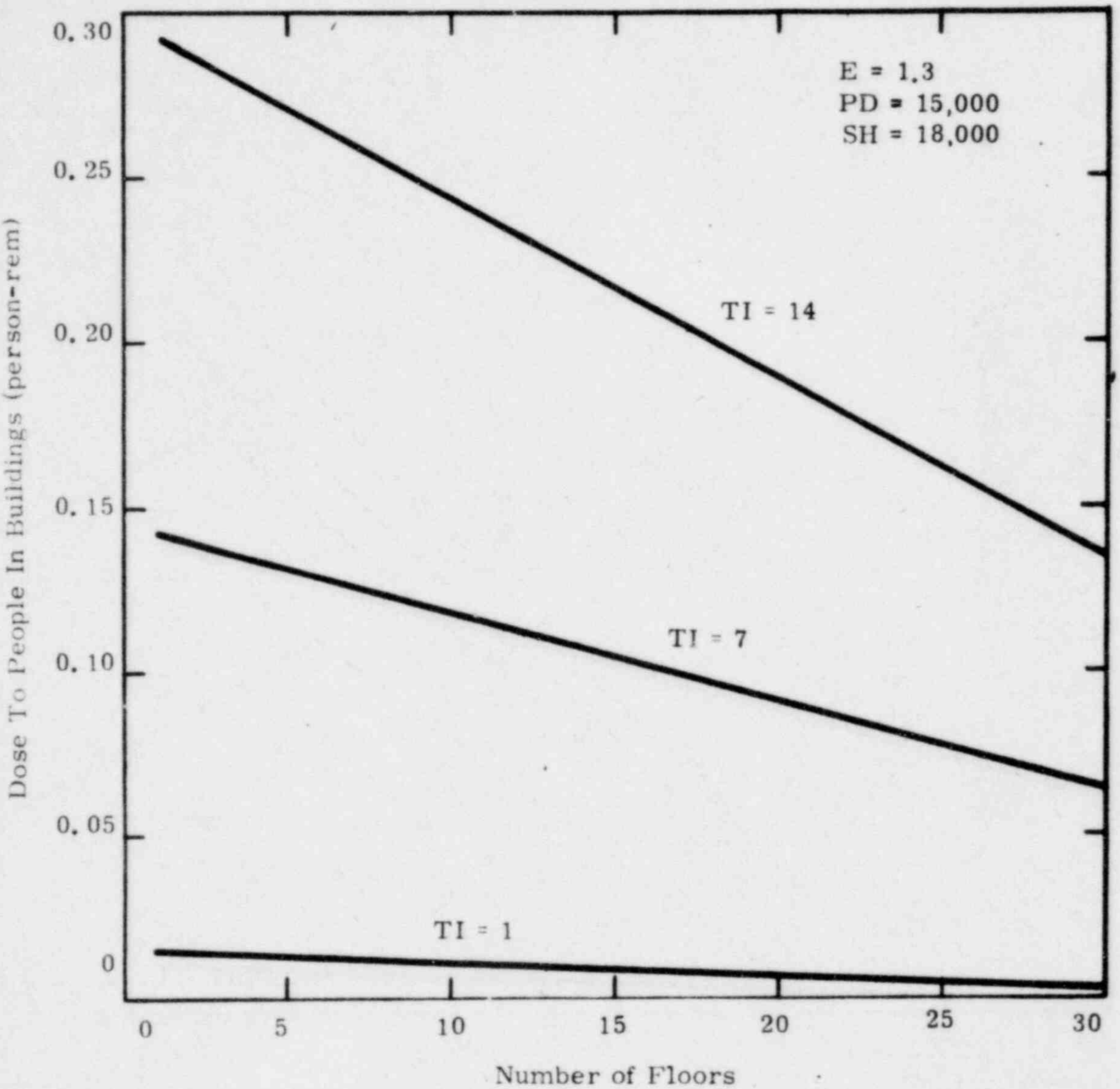


Figure 59. Dose to People in Buildings vs Number of Floors - Showing Effect of TI - TS-4

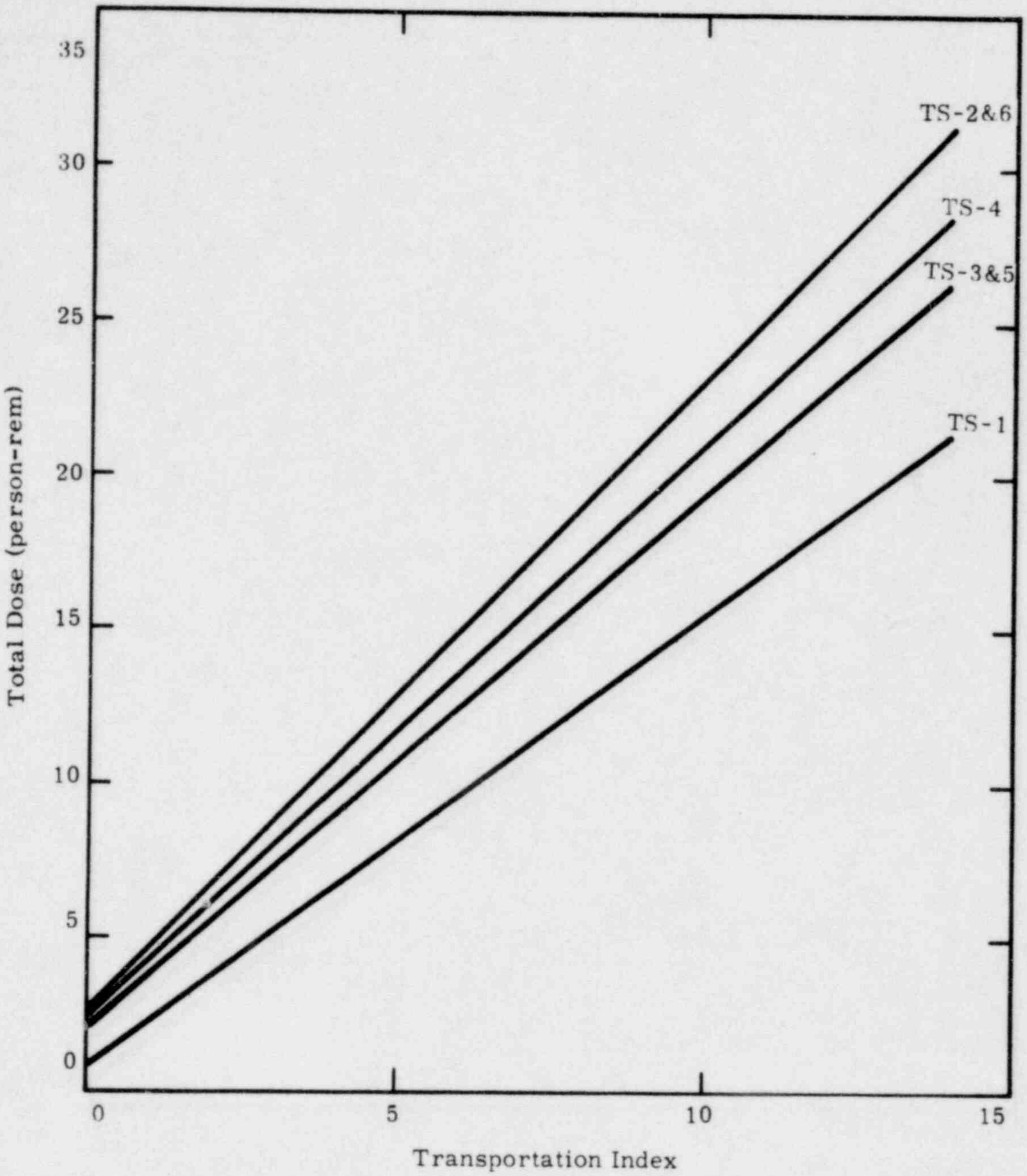


Figure 60. Total Dose vs Transportation Index

APPENDIX A

Urban Area Data Base

1. Introduction

In order to analyze the environmental impact of transportation of radioactive material in high density urban areas, an extensive data base is required. The data base for this project was obtained from governmental agencies, private industry, appropriate literature, and conversations with experts in the areas of interest. This appendix lists methods for the derivation of each parameter, assumptions if any, sources of information, and all values for each parameter.

Section 2 discusses the method used to divide the day into appropriate time intervals.

Section 3 discusses an urban area from the point of view of land use. Parameters considered here include:

1) The study area itself, how it was chosen, and division of the area into unit cells for study;
2) Amount of open area within the unit cells;
3) Amount of area devoted to buildings;
4) Amount of area devoted to streets and sidewalks; and
5) Other related parameters such as street width, sidewalk width, and number of lanes per side of street.

Section 4 discusses characteristics of buildings within the study area. These include building heights (number of floors per building times height per floor), wall thicknesses for different kinds of buildings, construction materials, and ventilation system characteristics.

Section 5 considers population characteristics of the urban area. One important characteristic is the large diurnal population fluctuation which typically occurs in an urban area. This section also concerns itself with population densities, pedestrian densities, and the number of persons in the area for non-work related reasons.

Section 6 addresses transportation parameters such as traffic counts, vehicle and pedestrian velocities, average vehicle length, average number of persons per vehicle, and average distances between moving vehicles (separation distances). Some additional transportation parameters with less variation across the study area include:

1) The length of time a vehicle is delayed at a typical urban intersection traffic signal;
2) The number of intersection stops made by vehicles during a typical trip (this obviously varies with the time of day);
3) Separation distance for vehicles stopped at intersections (as distinguished from moving vehicle separation distance); and,
4) Parameters related to freeway travel.

In the case of rail transport, parameters considered are the number of trains per hour passing through a terminal area, the distances of minimum and/or maximum approach of persons to the trains, speed of travel within the terminal area, and population densities in the terminal area. Air transport by either cargo or passenger aircraft and watercraft transport are treated in a similar fashion.

Section 7 discusses shipment characteristics including shipment route, roadway type, shipment model, package type, number of packages, destinations, and transport indices.

All of the above input data are necessary to evaluate the impact of transport under accident-free conditions. Several other parameters are necessary to evaluate the impact of transport under accident conditions.

Section 8 discusses the determination of accident rates by accident severity using the concepts established in Reference 1. This section also discusses methods used to estimate the amount of time a vehicle may be delayed by an accident.

Section 9 discusses dosimetric parameters such as photon energy and material toxicity.

Section 10 considers the unique characteristics of urban area meteorology. The meteorological information consists of typical hourly wind directions and speeds.

2. Time-Span Specification

Because most data are unavailable on an hourly basis, the 24-hour day has been divided along the lines of an urban day:

Time Span	Hours	Description
1	1800-0700	Nighttime
2	0700-0800	Morning rush period
3	0800-1130	Morning work period
4	1130-1300	Noon hour period
5	1300-1630	Afternoon work period
6	1630-1800	Afternoon rush period

Time-dependent data are presented as hourly average values for each of the six time spans. A seventh time span, indicated as "special" is included to allow introduction of instances of extremely high population and/or pedestrian densities which might result from special events such as baseball games, parades, concerts, etc.

3. Land Use Data

3.1 Basic Grid

The geographical area under consideration is a 10 km x 10 km grid encompassing portions of the New York City boroughs of Manhattan, Queens and Brooklyn. This grid was selected to cover the maximum amount of land area with as much variation of land use as possible within computational constraints. The area was further subdivided to produce the grid consisting of 100 1 km x 1 km cells shown in Figure 1. The squares are numbered from left to right and from top to bottom. Cell 1 is in the upper left corner; and cell 100 is in the lower right corner.

3.2 Open Area

It was necessary to convert much information on land use from other sources to the specified grid. A small grid overlay was prepared to allow for subdivision of the grid squares. The open area for each grid cell was obtained using this overlay and a square counting technique. Open area is characterized on maps in Reference 2 by variations in shading.

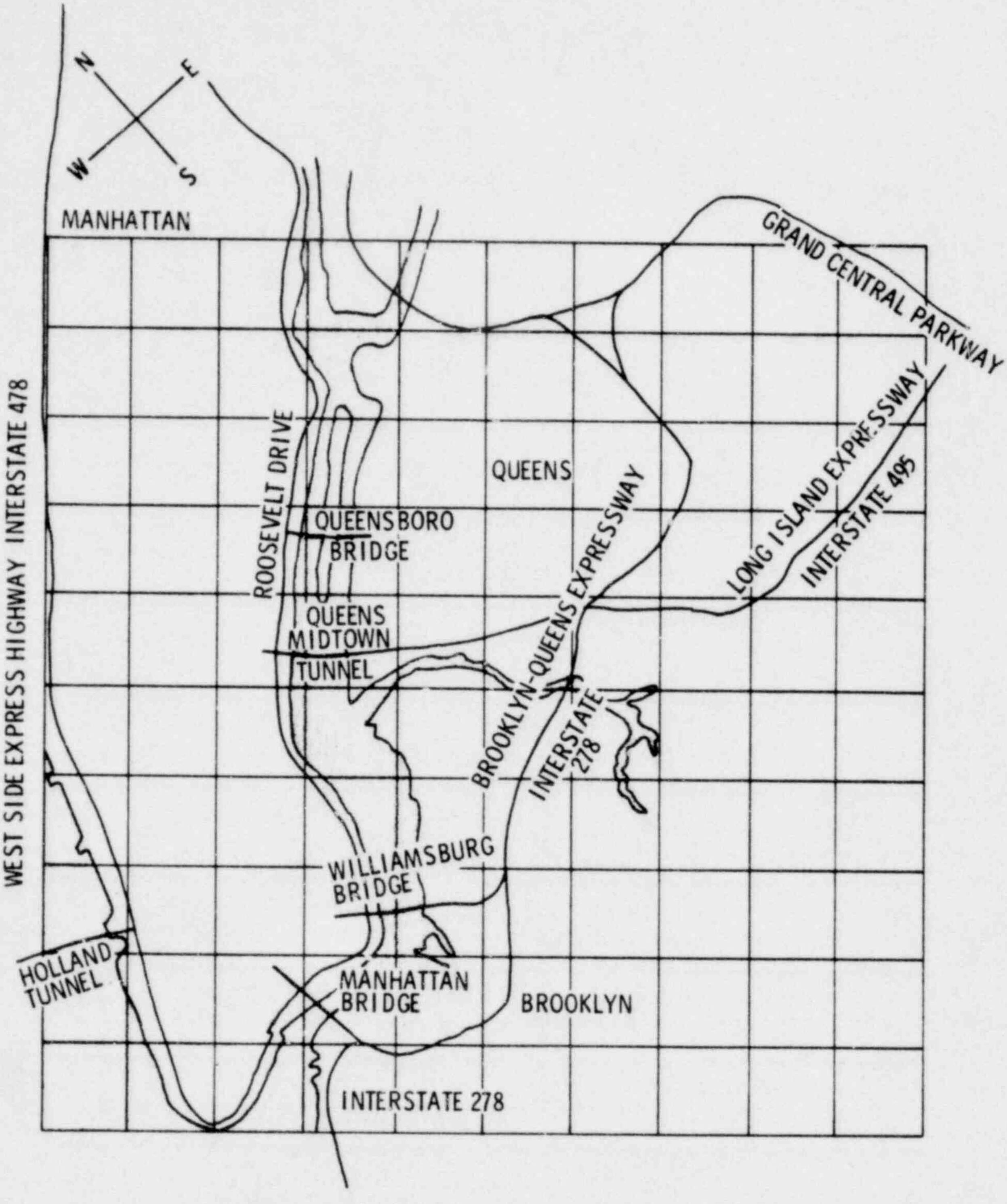


Figure 1. Basic Grid for Portions of Manhattan, Queens, and Brooklyn

3.3 Street Area

The fraction of each grid cell occupied by streets was determined by combining information on New York City Community Planning Districts (CPD)[3*] with information on street areas in New York City Health Areas.** Pertinent CPD's range in size from 0.59 to 10.52 km^2 (see Table 3), and square-counting techniques were used to determine the area of each affected CPD and the fraction of each grid cell occupied by a particular CPD. Health and street data were apportioned among the CPD's and subsequently to each grid cell.

The fraction of the grid square not occupied by open area or streets is assumed to be occupied by buildings. Values for open area, street area, and building area are tabulated in Table 1.

*In 1968, the City Planning Commission delineated 62 "Community Planning Districts." Each CPD has an administrative planning board which advises the borough president and city agencies on planning issues.

**A tabulation of street area (in acres) in each of the city's Health Areas is available at the office of the New York City Planning Commission. Using the square counting approach, Health Area data on street area were converted to street areas for CPD's and then to the grid itself. This information was subsequently used to obtain the fraction of each grid square occupied by streets. Information on population and street areas for the New York City Health Areas followed the 1970 Census tracts. Data used in this study were obtained in 1976 and reflect the 1970 census information. Subsequent to the acquisition of these data, the Community Planning District format for health care planning in New York City was established and work is currently going on to align the Health Area and larger Health Districts along the CPD boundaries.

TABLE 1
CELL AREA DISTRIBUTION

CELL NO.	OPEN	STREETS	BUILDINGS	CELL NO.	OPEN	STREETS	BUILDINGS
1	.000	.243	.757	51	.200	.363	.437
2	.700	.135	.165	52	.000	.433	.567
3	.200	.319	.481	53	.200	.342	.458
4	1.000	0.000	0.000	54	.700	.189	.111
5	.000	.342	.658	55	.000	.408	.592
6	.000	.289	.711	56	.000	.356	.644
7	.000	.399	.601	57	.200	.292	.508
8	.000	.334	.666	58	.000	.321	.679
9	.000	.338	.662	59	.000	.379	.621
10	.000	.309	.691	60	.100	.231	.669
11	.000	.200	.800	61	.500	.240	.260
12	.600	.142	.258	62	.000	.461	.539
13	.100	.404	.496	63	.000	.401	.599
14	.500	.254	.246	64	.500	.237	.263
15	.000	.385	.615	65	.000	.399	.601
16	.000	.448	.552	66	.000	.434	.566
17	.000	.411	.589	67	.000	.328	.672
18	.000	.424	.576	68	.000	.418	.582
19	.000	.414	.586	69	.000	.416	.584
20	.000	.398	.602	70	.600	.226	.174
21	.000	.331	.669	71	.700	.105	.195
22	.600	.141	.259	72	.027	.137	.836
23	.100	.405	.495	73	.000	.474	.526
24	400	.191	.409	74	.400	.222	.378
25	.000	.405	.595	75	.200	.468	.332
26	500	.402	.098	76	.000	.485	.515
27	.000	.460	.540	77	.000	.443	.557
28	.000	.467	.533	78	.000	.419	.581
29	.000	.431	.569	79	.000	.414	.586
30	.000	.365	.635	80	.600	.336	.064
31	.000	.354	.646	81	.800	0.000	.200
32	.200	.213	.587	82	.100	.367	.533
33	.200	.330	.470	83	.197	.335	.468
34	.300	.193	.507	84	.400	.151	.449
35	.300	.368	.332	85	.077	.147	.776
36	.100	.295	.605	86	.000	.410	.590
37	.000	.274	.726	87	.000	.416	.584
38	.000	.368	.632	88	.000	.407	.593
39	.000	.407	.593	89	.000	.400	.600
40	.000	.339	.661	90	.000	.439	.561
41	.000	.427	.573	91	1.000	0.000	0.000
42	.000	.393	.607	92	.300	.262	.438
43	.300	.240	.460	93	.500	.210	.290
44	.300	.271	.429	94	.500	.399	.101
45	.200	.352	.448	95	.000	.402	.598
46	.000	.296	.704	96	.000	.435	.565
47	.000	.239	.761	97	.000	.413	.587
48	.000	.317	.683	98	.000	.398	.602
49	.000	.303	.697	99	.000	.410	.590
50	.000	.319	.681	100	.000	.399	.601

3.4 Other Land Use Parameters

Other land use parameters include sidewalk width, street width, number of lanes per side of street, and block length. The following constant values, reflecting reasonable standards for metropolitan areas[4], were selected for these parameters:

Street width	20 m
Sidewalk width	3 m
No. of lanes/side of street	4
Block length	200 m.

4. Building Characteristics

Average building height information was estimated on the basis of personal observation and aerial photographic data[2]. Average building height per cell is indicated by the number of floors per building, assuming a constant height per floor of 3 meters. Thus a 20-floor building is assumed to be 60 m high. An architect[5] estimated that older residential buildings with exterior supporting walls would have wall thicknesses averaging .38 m (15 in.). Newer buildings with skeleton support, i.e., support for the building from the skeleton, not the walls alone, would have wall thicknesses on the order of .20 m (8 in.). If a grid cell has an average building height less than 24 m, it is assumed to be mostly residential and to have wall thicknesses of .38 m. Grid cells characterized by buildings taller than 24 m are assumed to contain structures having a wall thickness of 0.20 m. Data for building height and wall thickness are given in Table 2.

Wood, concrete and brick construction materials are considered. For the study area under consideration, the absorption of radiation in building materials is assumed to be that of concrete.

TABLE 2
BUILDING CHARACTERISTICS

CELL NO.	NO.OF STORIES	WALL THICKNESS (M)
1	5	.380
2	6	.380
3	7	.380
4	3	.380
5	3	.380
6	5	.380
7	5	.380
8	3	.380
9	5	.380
10	3	.380
11	6	.380
12	5	.380
13	6	.380
14	5	.380
15	4	.380
16	6	.380
17	5	.380
18	5	.380
19	4	.380
20	3	.380
21	7	.380
22	5	.380
23	7	.380
24	15	.203
25	4	.380
26	5	.380
27	5	.380
28	4	.380
29	3	.380
30	3	.380
31	9	.203
32	30	.203
33	9	.203
34	10	.203
35	2	.380
36	5	.380
37	4	.380
38	5	.380
39	3	.380
40	5	.380
41	7	.380
42	30	.203
43	20	.203
44	15	.203
45	3	.380
46	5	.380
47	4	.380
48	5	.380
49	5	.380
50	5	.380

CELL NO.	NO.OF STORIES	WALL THICKNESS (M)
51	10	.203
52	20	.203
53	7	.380
54	15	.203
55	3	.380
56	4	.380
57	10	.203
58	5	.380
59	5	.380
60	4	.380
61	4	.380
62	7	.380
63	10	.203
64	7	.380
65	5	.380
66	3	.380
67	10	.203
68	3	.380
69	4	.380
70	3	.380
71	3	.380
72	15	.203
73	7	.380
74	9	.203
75	5	.380
76	3	.380
77	10	.203
78	3	.380
79	3	.380
80	4	.380
81	1	.380
82	30	.203
83	9	.203
84	7	.380
85	3	.380
86	4	.380
87	3	.380
88	5	.380
89	3	.380
90	3	.380
91	0	.380
92	50	.203
93	30	.203
94	5	.380
95	5	.380
96	3	.380
97	3	.380
98	3	.380
99	3	.380
100	3	.380

The building air change rate (R) is required in calculating the exposure to people inside buildings for a passing cloud of radioactive debris. (See Equations 22 and 23 of Appendix E.) Values for the parameter for single-family dwellings can be found in the literature.[6-11] In general, the air change rate ranges from 0.5[6] to 6.0[8] per hour. Values for large structures such as apartment buildings, office buildings, etc. are less well documented, although a range from 0.2[7] (total recirculation) to 9.0[8] changes per hour are suggested. Although the range is large, most values for both residences and larger structures are between 1.5 and 3.0 changes per hour. Since dose is proportional to the value selected for air change rate, a value of 3.0 changes per hour is used for all structure types to make the calculation conservative.

5. Population Parameters

5.1 Population Density

One of the significant characteristics of an urban area is the large diurnal variation in population density. To calculate population densities, the area in square kilometers for each pertinent CPD was determined by the square counting technique. The total populations for the CPD's were available from New York City Planning Commission data.[3] From this information, population densities were determined. Values are listed in Table 3.

TABLE 3

POPULATION DENSITY IN PERTINENT CPD'S

CPD	Area (Km^2)	Population	Population Density (PD) (Persons/Km^2)
MANHATTAN			
1	2.64	7,034	2,967
2	2.36	85,357	35,750
3	2.94	182,171	61,963
4	3.25	83,857	25,802
5	2.86	31,458	10,997
6	2.36	121,886	51,646
7	3.33	212,316	63,629
8	3.50	200,189	54,194
11	2.64	154,450	58,504
BROOKLYN			
1	7.94	179,458	23,736
2	3.04	73,609	24,213
3	6.08	216,983	35,688
4	3.33	137,895	41,369
BNY (Brooklyn) Naval Yard)	0.59	1,134	1,902
QUEENS			
1	10.52	194,384	18,097
2	9.59	124,146	13,994
3	5.11	123,598	24,101
4	3.66	107,961	27,694
5	6.10	125,167	20,519
6	5.80	119,019	20,521

If a particular grid cell was entirely within a single CPD, the population density was set equal to that CPD population density. If the cell overlapped more than one CPD or part of some body of water, the population density for the cell was computed by taking the fraction of the square occupied by each CPD and multiplying by the appropriate population density. The fractional population densities were then summed to obtain an average value for the cell. Table 4 indicates the manner in which this calculation was accomplished using data for cell 62.

TABLE 4

SAMPLE CALCULATION OF POPULATION DENSITY

CPD (Manhattan)	Fraction of Cell Occupied by Each CPD	Population Density for CPD's
2	0.7	35,750
4	0.2	25,802
5	0.1	10,997

Population Density for Cell No. 62 = (0.1 x 10,997) + (0.2 x 25,802) + (0.7 x 35,750) =

31,278 People/km^2

The calculation shown in Table 4 determines the resident population of the cells. These resident population densities are considered applicable to the nighttime (Time Span 1) division of the urban day. To calculate daytime population densities, values for the number of persons over 16 years of age who were employed in each CPD, information on the percentage of workers residing in a borough who work in that borough, and information on the number of workers who commute to a borough to work were obtained from Reference 12. Reference 2 provided information on the designation of a grid cell as residential, commercial, industrial or mixed. This designation was used to estimate the number of resident workers who remained in the cell and the number commuting out of the cell to work. For example:

Cell No. 1

Average population density: 63,629

Resident workers: 36,077

Percentage of workers living in Manhattan that work in Manhattan: 71.7%

Number of residents in cell that work in Manhattan:

.717 * 36,077 = 25,650

It is assumed that 20 percent of the residents of the cell, working in Manhattan, remain within the cell to work. Thus the number of resident workers remaining in the cell = 5130. Cell No. 1 is principally residential[2], hence, during the day, most of the residents who work leave the cell. The number of resident workers remaining in the cell is added to the non-working population to obtain values for daytime population density.

Census data[12] provided information on the total number of commuters coming into the borough to work. The total number of persons who commute to the grid was distributed among the cells by considering the cell designation (residential, commercial, industrial, or mixed). Similarly, the total number of persons who commute out of the grid from each borough was distributed among the cells in each borough. This net commuter flux was added to (or subtracted from) the daytime resident population to obtain a more realistic figure for average total daytime population. Nighttime figures are set equal to the total resident population density. Table 5 lists values for population density in different time spans for each cell.

5.2 Pedestrian Density

Determination of pedestrian densities required a different approach. Table 3.8 in Reference 13 lists characteristics of pedestrian flow in terms of effective space occupied by a single pedestrian (m^2/pedestrian). The six time spans were estimated to correspond to varying degrees of pedestrian flow and are given, with effective spaces, in Table 6. These effective spaces result from the assumption that large groups of pedestrians form during normal pedestrian flow.

TABLE 5
POPULATION DENSITY
(PERSONS/SQ.KM.)
T-I-M-E S-P-A-N

CELL NO.	1	2	3	4	5	6
1	63629.	48155.	32682.	32682.	32682.	48155.
2	17551.	15308.	13065.	13065.	13065.	15308.
3	46832.	40846.	34861.	34861.	34861.	40846.
4	0.	0.	0.	0.	0.	0.
5	18079.	14287.	10496.	10496.	10496.	14287.
6	18097.	14430.	10763.	10763.	10763.	14430.
7	21099.	21304.	21510.	21510.	21510.	21304.
8	61973.	48160.	34357.	34357.	34357.	48160.
9	24101.	18698.	13296.	13296.	13296.	18698.
10	20718.	16083.	11449.	11449.	11449.	16083.
11	63629.	48155.	32682.	32682.	32682.	48155.
12	17158.	12985.	8812.	8812.	8812.	12985.
13	51474.	38956.	26438.	26438.	26438.	38956.
14	9048.	7214.	5381.	5381.	5381.	7214.
15	18079.	14287.	10496.	10496.	10496.	14287.
16	18097.	14430.	10763.	10763.	10763.	14430.
17	16645.	13023.	9401.	9401.	9401.	13023.
18	61973.	48160.	34357.	34357.	34357.	48160.
19	26256.	20536.	14816.	14816.	14816.	20536.
20	27694.	21835.	15977.	15977.	15977.	21835.
21	63629.	48155.	32682.	32682.	32682.	48155.
22	17158.	12985.	8812.	8812.	8812.	12985.
23	51474.	38956.	26438.	26438.	26438.	38956.
24	10858.	18250.	25643.	25643.	25643.	18250.
25	18079.	24529.	30979.	30979.	30979.	24529.
26	9048.	16807.	24567.	24567.	24567.	16807.
27	13994.	10876.	7759.	7759.	7759.	10876.
28	30771.	24084.	17398.	17398.	17398.	24084.
29	27694.	21335.	15977.	15977.	15977.	21835.
30	23390.	18195.	13001.	13001.	13001.	18195.
31	38411.	89089.	139768.	139768.	139768.	89089.
32	15177.	67855.	120533.	120533.	120533.	67855.
33	42426.	31377.	20329.	20329.	20329.	31377.
34	7627.	16097.	24568.	24568.	24568.	16097.
35	12668.	20396.	28124.	28124.	28124.	20396.
36	16287.	23657.	31027.	31027.	31027.	23657.
37	13994.	10876.	7759.	7759.	7759.	10876.
38	35740.	27778.	19817.	19817.	19817.	27778.
39	18691.	14623.	10556.	10556.	10556.	14623.
40	20519.	16390.	12261.	12261.	12261.	16390.
41	25802.	19394.	129696.	129696.	129696.	19394.
42	10997.	63958.	116920.	116920.	116920.	63958.
43	36152.	86868.	137585.	137585.	137585.	86868.
44	7627.	16097.	24568.	24568.	24568.	16097.
45	10037.	18360.	26684.	26684.	26684.	18360.
46	18097.	24650.	31023.	31023.	31023.	24650.
47	13994.	11516.	9039.	9039.	9039.	11516.
48	35740.	27778.	19817.	19817.	19817.	27778.
49	17256.	13629.	10004.	10004.	10004.	13629.
50	20519.	16466.	12414.	12414.	12414.	16466.

CELL NO.	1	2	3	4	5	6
51	20641.	83026.	124470.	124770.	124770.	83026.
52	15438.	68150.	120863.	120863.	120863.	68150.
53	41316.	91568.	141821.	141821.	141821.	91568.
54	7129.	12883.	18638.	18638.	18638.	12883.
55	23736.	32778.	41820.	41820.	41820.	32778.
56	23736.	34050.	44364.	44364.	44364.	34050.
57	16066.	19065.	22065.	22065.	22065.	19065.
58	25842.	25143.	24444.	24444.	24444.	25143.
59	20519.	16466.	12414.	12414.	12414.	16466.
60	18467.	14820.	11174.	11174.	11174.	14820.
61	15882.	68807.	121733.	121733.	121733.	68807.
62	31278.	83210.	135142.	135142.	135142.	83210.
63	58867.	104723.	150580.	150580.	150580.	104723.
64	30918.	27593.	24268.	24268.	24268.	27593.
65	23736.	34332.	44928.	44928.	44928.	34332.
66	23736.	24544.	25352.	25352.	25352.	24544.
67	23736.	33096.	42456.	42456.	42456.	33096.
68	35290.	29985.	24680.	24680.	24680.	29985.
69	40232.	33273.	26315.	26315.	26315.	33273.
70	8207.	6586.	4965.	4965.	4965.	6586.
71	7745.	7293.	6842.	6842.	6842.	7293.
72	32463.	84428.	136394.	136394.	136394.	84428.
73	50522.	62525.	74529.	74529.	74529.	62525.
74	37177.	31469.	25761.	25761.	25761.	31469.
75	18988.	21507.	24027.	24027.	24027.	21507.
76	24931.	25587.	26244.	26244.	26244.	25587.
77	33806.	37542.	41279.	41279.	41279.	37542.
78	39664.	35041.	30419.	30419.	30419.	35041.
79	35688.	30703.	25718.	25718.	25718.	30703.
80	16547.	14250.	11954.	11954.	11954.	14250.
81	593.	561.	530.	530.	530.	561.
82	2670.	56490.	110311.	110311.	110311.	56490.
83	25972.	40919.	55866.	55866.	55866.	40919.
84	22267.	20651.	19036.	19036.	19036.	20651.
85	8405.	19770.	31136.	31136.	31136.	19770.
86	32197.	34477.	36758.	36758.	36758.	34477.
87	35688.	34852.	34016.	34016.	34016.	34852.
88	35668.	30611.	25554.	25554.	25554.	30611.
89	36000.	30888.	25777.	25777.	25777.	30888.
90	35688.	30637.	25586.	25586.	25586.	30637.
91	0.	0.	0.	0.	0.	0.
92	2077.	28960.	55843.	55843.	55843.	28960.
93	1483.	28364.	55245.	55245.	55245.	28364.
94	24213.	24871.	25530.	25530.	25530.	24871.
95	24123.	70289.	116455.	116455.	116455.	70289.
96	24213.	23572.	22931.	22931.	22931.	23572.
97	35688.	30621.	25554.	25554.	25554.	30621.
98	35688.	30653.	25618.	25618.	25618.	30653.
99	36700.	30757.	25514.	25514.	25514.	30757.
100	35688.	30637.	27875.	27875.	27875.	30637.

TABLE 6

CHARACTERISTICS OF PEDESTRIAN FLOW

Time Span	Pedestrian Flow	Square meters/ Pedestrian
1 nighttime	Unlimited*	24.7
2 morning rush	Constrained	2.95
3. morning work	Impeded	4.65
4 noontime	Congested	1.25
5 afternoon work	Impeded	4.65
6 afternoon rush	Constrained	2.95

*The value for this time span is based on weighted averages reflecting changes in pedestrian flow for evening, late night and early morning hours.

Land use data provide the fraction of each grid square occupied by streets. The total sidewalk area for a grid square, assuming each street has sidewalks on each side, is given by:

$$\text{Total sidewalk area in } m^2 = \frac{f_{st} * 10^6}{w_{st}} * 2\, w_s \, , \qquad (1)$$

where w_{st} = street width (m)

f_{st} = fraction of grid cell occupied by streets

w_s = sidewalk width (m).

Therefore,

$$\underset{\text{(Ped D)}}{\text{Total Pedestrians}} = \frac{f_{st} * 10^6}{w_{st}} * 2\, w_s \quad \frac{\ }{\ } \quad \begin{array}{l}\text{effective space}\\ \text{per pedestrian.}\end{array}$$

Since there are six time intervals, six values for pedestrian density are obtained as indicated by the sample calculation in Table 7. In this case f_{st} = 0.243 (0.243 km^2 of the cell is occupied by streets), w_{st} = 20 m, and w_s = 3 m so, the total sidewalk area is 7.3 x 10^4 m^2 and the resulting pedestrian densities are:

TABLE 7

PEDESTRIAN DENSITIES FOR DIFFERENT TIME SPANS IN CELL NO. 1

Time Span	Pedestrian Density (No. people/km^2 of sidewalk)
1	2,951
2	24,712
3	15,677
4	58,320
5	15,677
6	24,712

This calculation presumes uniform distribution of pedestrians on all sidewalks within the grid square. Values for pedestrian density for all grid squares are summarized in Table 8.

TABLE F
PEDESTRIAN DENSITY
(PERSONS/SQ.KM.OF SIDEWALK)
T-I-M-E S-P-A-N

CELL NO.	1	2	3	4	5	6
1	2951.	24712.	15677.	58320.	15677.	24712.
2	1640.	13729.	8710.	32400.	8710.	13729.
3	3874.	32441.	20581.	76560.	20581.	32441.
4	0.	0.	0.	0.	0.	0.
5	4154.	34780.	22065.	82080.	22065.	34780.
6	3510.	29390.	18645.	69360.	18645.	29390.
7	4846.	40576.	25742.	95760.	25742.	40576.
8	4057.	33966.	21548.	80160.	21548.	33966.
9	4105.	34373.	21806.	81120.	21806.	34373.
10	3753.	31424.	19935.	74160.	19935.	31424.
11	2729.	20339.	12903.	48000.	12903.	20339.
12	1725.	14441.	9161.	34080.	9161.	14441.
13	4907.	41085.	26064.	96960.	26064.	41085.
14	3085.	25835.	16387.	60960.	16387.	25835.
15	4676.	39155.	24839.	92400.	24839.	39155.
16	5441.	45559.	28903.	107520.	28903.	45559.
17	4992.	41797.	26516.	98640.	26516.	41792.
18	5150.	43119.	27355.	101760.	27355.	43119.
19	5028.	42102.	26710.	99360.	26710.	42102.
20	4834.	40475.	25677.	95520.	25677.	40475.
21	4020.	33661.	21355.	79440.	21355.	33661.
22	1713.	14339.	9097.	33840.	9097.	14339.
23	4919.	41186.	26129.	97200.	26129.	41186.
24	2320.	19424.	12323.	45840.	12323.	19424.
25	4919.	41186.	26129.	97200.	26129.	41186.
26	4883.	40881.	25936.	96480.	25936.	40881.
27	5587.	46780.	29677.	110400.	29677.	46780.
28	5672.	47492.	30129.	112080.	30129.	47492.
29	5235.	43831.	27807.	103440.	27807.	43831.
30	4433.	37119.	23548.	87600.	23548.	37119.
31	4300.	36000.	22839.	84960.	22839.	36000.
32	2587.	21661.	13742.	51120.	13742.	21661.
33	4008.	33559.	21290.	79200.	21290.	33559.
34	2344.	19627.	12452.	46320.	12452.	19627.
35	4470.	37424.	23742.	88320.	23742.	37424.
36	3583.	30000.	10932.	70800.	10932.	30000.
37	3328.	27864.	17677.	65760.	17677.	27864.
38	4470.	37424.	23742.	88320.	23742.	37424.
39	4943.	41390.	26258.	97680.	26258.	41390.
40	4117.	34475.	21871.	81360.	21871.	34475.
41	5186.	43424.	27548.	102480.	27548.	43424.
42	4773.	39966.	25355.	94320.	25355.	39966.
43	2915.	24407.	15484.	57600.	15484.	24407.
44	3292.	27559.	17484.	65040.	17484.	27559.
45	4275.	35797.	22710.	84480.	22710.	35797.
46	3595.	30102.	19097.	71040.	19097.	30102.
47	2903.	24305.	15419.	57360.	15419.	24305.
48	3850.	32237.	20452.	76080.	20452.	32237.
49	3680.	30814.	19548.	72720.	19548.	30814.
50	3874.	32441.	20581.	76560.	20581.	32441.
51	4409.	36915.	23419.	87120.	23419.	36915.
52	5259.	44034.	27936.	103920.	27936.	44034.
53	4154.	34780.	22065.	82080.	22065.	34780.
54	2296.	19220.	12194.	45360.	12194.	19220.
55	4955.	41492.	26323.	97920.	26323.	41492.
56	4324.	36203.	22968.	85440.	22968.	36203.
57	3547.	29695.	18839.	70080.	18839.	29695.
58	3699.	32644.	20710.	77040.	20710.	32644.
59	4603.	38542.	24452.	90960.	24552.	38542.
60	2806.	23492.	14903.	55440.	14903.	23492.
61	2915.	24407.	15484.	57600.	15484.	24407.
62	5599.	46881.	29742.	110640.	29742.	46881.
63	4870.	40780.	25871.	96240.	25871.	40780.
64	2879.	24102.	15290.	56880.	15290.	24102.
65	4846.	40576.	25742.	95760.	25742.	40576.
66	5271.	44136.	28000.	104160.	28000.	44136.
67	3984.	33356.	21161.	78720.	21161.	33356.
68	5077.	42508.	26968.	100320.	26968.	42508.
69	5053	42305.	26839.	99840.	26839.	42305.
70	2745.	22983.	14581.	54240.	14581.	22983.
71	1275.	10678.	6774.	25200.	6774.	10678.
72	1664.	13932.	8839.	32880.	8839.	13932.
73	5757.	48203.	30581.	113760.	30581.	48203.
74	2696.	22576.	14323.	53280.	14323.	22576.
75	5684.	47593.	30194.	112320.	30194.	47593.
76	5891.	49322.	31290.	116400.	31290.	49322.
77	5381.	45051.	28581.	106320.	28581.	45051.
78	3089.	42610.	27032.	100560.	27032.	42610.
79	5028.	42102.	26710.	99360.	26710.	42102.
80	4081.	34170.	21677.	80640.	21677.	34170.
81	0.	0.	0.	0.	0.	0.
82	4457	37322.	23677.	88080.	23677.	37322.
83	4069.	34068.	21613.	80400.	21613.	34068.
84	1834.	15356.	9742.	36240.	9742.	15356.
85	1785.	14949.	9484.	35280.	9484.	14949.
86	4980.	41694.	26452.	98400.	26452.	41694.
87	5053.	42305.	26839.	99840.	26839.	42305.
88	4943.	41390.	26258.	97680.	26258.	41390.
89	4858.	40678.	25807.	96000.	25807.	40678.
90	5332.	44644.	28323.	105360.	28323.	44644.
91	0.	0.	0.	0.	0.	0.
92	3182.	26644.	16903.	62800.	16903.	26644.
93	2551.	21356.	13548.	50400.	13548.	21356.
94	4846.	40576.	25742.	95760.	25742.	40576.
95	4883.	40881.	25936.	96480.	25936.	40881.
96	5283.	44237.	28065.	104400.	28065.	44237.
97	5016.	42000.	26645.	99120.	26645.	42000.
98	4834.	40475.	25677.	95520.	25677.	40475.
99	4980.	41675.	26452.	98400.	26452.	41675.
100	4846.	40576.	25742.	95760.	25742.	40576.

within buildings during the daytime hours. This may count some people twice since the values for traffic count and pedestrian density clearly include some of the transient clientele. A summary of transient clientele data is shown in Table 9. This calculation does not account for people who would come into the area in the evening for entertainment purposes. This factor should eventually be incorporated in the calculation of transient clientele for evening hours.

TABLE 9
TRANSIENT CLIENTELE
(PERSONS/SQ.KM.)
T-I-M-E S-P-A-N

CELL NO.	1	2	3	4	5	6
1	0.	3075.	3075.	3075.	3075.	3075.
2	0.	803.	803.	803.	803.	803.
3	0.	2734.	2734.	2734.	2734.	2734.
4	0.	0.	0.	0.	0.	0.
5	0.	1598.	1598.	1598.	1598.	1598.
6	0.	2888.	2888.	2888.	2888.	2888.
7	0.	2442.	2442.	2442.	2442.	2442.
8	0.	1622.	1622.	1622.	1622.	1622.
9	0.	2685.	2685.	2685.	2685.	2685.
10	0.	1679.	1679.	1679.	1679.	1679.
11	0.	3894.	3894.	3894.	3894.	3894.
12	0.	1046.	1046.	1046.	1046.	1046.
13	0.	2418.	2418.	2418.	2418.	2418.
14	0.	998.	998.	998.	998.	998.
15	0.	1996.	1996.	1996.	1996.	1996.
16	0.	2685.	2685.	2685.	2685.	2685.
17	0.	2393.	2393.	2393.	2393.	2393.
18	0.	2336.	2336.	2336.	2336.	2336.
19	0.	1898.	1898.	1898.	1898.	1898.
20	0.	1468.	1468.	1468.	1468.	1468.
21	0.	3797.	3797.	3797.	3797.	3797.
22	0.	1055.	1055.	1055.	1055.	1055.
23	0.	2815.	2815.	2815.	2815.	2815.
24	0.	4981.	4981.	4981.	4981.	4981.
25	0.	1931.	1931.	1931.	1931.	1931.
26	0.	397.	397.	397.	397.	397.
27	0.	2190.	2190.	2190.	2190.	2190.
28	0.	1728.	1728.	1728.	1728.	1728.
29	0.	1387.	1387.	1387.	1387.	1387.
30	0.	1549.	1549.	1549.	1549.	1549.
31	0.	4713.	4713.	4713.	4713.	4713.
32	0.	14286.	14286.	14286.	14286.	14286.
33	0.	3432.	3432.	3432.	3432.	3432.
34	0.	4113.	4113.	4113.	4113.	4113.
35	0.	535.	535.	535.	535.	535.
36	0.	2458.	2458.	2458.	2458.	2458.
37	0.	2353.	2353.	2353.	2353.	2353.
38	0.	2564.	2564.	2564.	2564.	2564.
39	0.	1444.	1444.	1444.	1444.	1444.
40	0.	2685.	2685.	2685.	2685.	2685.
41	0.	3253.	3253.	3253.	3253.	3253.
42	0.	14773.	14773.	14773.	14773.	14773.
43	0.	7463.	7463.	7463.	7463.	7463.
44	0.	5224.	5224.	5224.	5224.	5224.
45	0.	1087.	1087.	1087.	1087.	1087.
46	0.	2855.	2855.	2855.	2855.	2855.
47	0.	2466.	2466.	2466.	2466.	2466.
48	0.	2775.	2775.	2775.	2775.	2775.
49	0.	2831.	2831.	2831.	2831.	2831.
50	0.	2766.	2766.	2766.	2766.	2766.

CELL NO.	1	2	3	4	5	6
51	0.	3545.	3545.	3545.	3545.	3545.
52	0.	9199.	9199.	9199.	9199.	9199.
53	0.	2604.	2604.	2604.	2604.	2604.
54	0.	1446.	1446.	1446.	1446.	1446.
55	0.	1444.	1444.	1444.	1444.	1444.
56	0.	2093.	2093.	2093.	2093.	2093.
57	0.	4121.	4121.	4121.	4121.	4121.
58	0.	2758.	2758.	2758.	2758.	2758.
59	0.	2523.	2523.	2523.	2523.	2523.
60	0.	2174.	2174.	2174.	2174.	2174.
61	0.	844.	844.	844.	844.	844.
62	0.	3058.	3058.	3058.	3058.	3058.
63	0.	4859.	4859.	4859.	4859.	4859.
64	0.	1493.	1493.	1493.	1493.	1493.
65	0.	2442.	2442.	2442.	2442.	2442.
66	0.	1379.	1379.	1379.	1379.	1379.
67	0.	5452.	5452.	5452.	5452.	5452.
68	0.	1420.	1420.	1420.	1420.	1420.
69	0.	1898.	1898.	1898.	1898.	1898.
70	0.	422.	422.	422.	422.	422.
71	0.	479.	479.	479.	479.	479.
72	0.	10173.	10173.	10173.	10173.	10173.
73	0.	2985.	2985.	2985.	2985.	2985.
74	0.	2758.	2758.	2758.	2758.	2758.
75	0.	1347.	1347.	1347.	1347.	1347.
76	0.	1257.	1257.	1257.	1257.	1257.
77	0.	4519.	4519.	4519.	4519.	4519.
78	0.	1412.	1412.	1412.	1412.	1412.
79	0.	1428.	1428.	1428.	1428.	1428.
80	0.	211.	211.	211.	211.	211.
81	0.	16.	16.	16.	16.	16.
82	0.	12972.	12972.	12972.	12972.	12972.
83	0.	3415.	3415.	3415.	3415.	3415.
84	0.	2547.	2547.	2547.	2547.	2547.
85	0.	1890.	1890.	1890.	1890.	1890.
86	0.	1915.	1915.	1915.	1915.	1915.
87	0.	1420.	1420.	1420.	1420.	1420.
88	0.	2409.	2409.	2409.	2409.	2409.
89	0.	1460.	1460.	1460.	1460.	1460.
90	0.	1363.	1363.	1363.	1363.	1363.
91	0.	0.	0.	0.	0.	0.
92	0.	17766.	17766.	17766.	17766.	17766.
93	0.	7058.	7058.	7058.	7058.	7058.
94	0.	414.	414.	414.	414.	414.
95	0.	2426.	2426.	2426.	2426.	2426.
96	0.	1379.	1379.	1379.	1379.	1379.
97	0.	1428.	1428.	1428.	1428.	1428.
98	0.	1468.	1468.	1468.	1468.	1468.
99	0.	1436.	1436.	1436.	1436.	1436.
100	0.	1460.	1460.	1460.	1460.	1460.

5.3 Transient Clientele

In addition to residents and pedestrians, there are people in each cell whose purposes may not be directly work-related. It is initially assumed that this "transient clientele" is significant only during the day. In Chapter 4 of Reference 13 it is indicated that for the Manhattan Central Business District 4.3 daily one-way trips are made for every 93 m^2 of floor space, regardless of floor space utilization and trip purpose. This value is assumed to be constant across the grid so the number of one-way trips for each cell can be estimated using the expression:

$$\text{No. of one-way trips} = \frac{f_b * n * 10^6 \text{ m}^2/\text{km}^2 * 1 \text{ km}^2 * 4.3 \text{ trips}}{93 \text{ m}^2} , \quad (2)$$

where f_b = fraction of grid squares occupied by buildings

n = average number of floors per building

For example, in cell No. 1 f_b = 0.757 and n = 5. Therefore, cell No. 1 generates 1.75×10^5 one-way trips per day.

Reference 4 (Chapter 5, p. 157) suggests that, in urban areas, 19.3% of all daily trips are specifically for non-work purposes (7.5% for shopping and 11.8% for miscellaneous purposes). The total number of one-way trips is multiplied by this fraction to obtain a figure for transient clientele. The figure obtained reflects the total value for eleven hours of the urban work day. An hourly figure is obtained by dividing the result by eleven. Therefore, 3075 trips per hour are made to grid cell No. 1 for non-work purposes. Since most of these trips are to buildings, it is assumed that all transient clientele are

6. Transportation Parameters

6.1 Traffic Count

Data from Reference 13 for traffic characteristics in an area of midtown Manhattan (cell No. 72) were considered typical for all cells in the geographical study area. Using differing degrees of traffic congestion as characteristics for different times of the day[13], the fraction of the cell occupied by streets, and assuming that the number of vehicles in a given cell is proportional to population density and street area, the number of vehicles present in each grid cell is calculated in direct proportion to the data for cell 72. (The method of calculation follows that for pedestrian density.) The mathematical model requires this information on an hourly basis and it is translated to that format using the following expression:

$$\text{Hourly traffic count} = \frac{N\bar{V}}{2\left(\frac{A * f_{st}}{w_{st}}\right)} \tag{3}$$

where N = the number of vehicles going in any direction at a given time

$\bar{V}$ = average vehicular speed (km/hour), including delays. (This information was acquired from Reference 3. For further information, see the derivation of vehicular speeds which follows.)

$A = 1\ km^2$, the area of a cell.

Data for hourly traffic counts are listed in Table 10.

TABLE 10
ONE WAY TRAFFIC COUNT
(VEHICLES/HR)
T-I-M-E S-P-A-N

CELL NO.	1	2	3	4	5	6
1	38.	315.	255.	170.	241.	315.
2	21.	125.	102.	68.	96.	125.
3	40.	333.	270.	180.	255.	333.
4	0.	0.	0.	0.	0.	0.
5	11.	96.	78.	52.	73.	96.
6	12.	103.	84.	56.	79.	103.
7	25.	207.	168.	112.	159.	207.
8	40.	331.	268.	179.	254.	331.
9	15.	128.	104.	69.	98.	128.
10	13.	110.	89.	59.	84.	110.
11	38.	315.	256.	170.	242.	315.
12	10.	85.	72.	46.	68.	85.
13	31.	255.	207.	138.	195.	255.
14	7.	52.	42.	28.	40.	52.
15	12.	101.	82.	55.	77.	101.
16	12.	104.	84.	56.	79.	104.
17	11.	91.	74.	49.	70.	91.
18	40.	331.	268.	179.	254.	331.
19	17.	143.	116.	77.	109.	143.
20	18.	154.	125.	83.	118.	154.
21	39.	315.	255.	170.	241.	315.
22	10.	85.	72.	46.	69.	85.
23	31.	254.	206.	138.	195.	254.
24	30.	247.	200.	133.	189.	247.
25	36.	298.	242.	161.	229.	298.
26	28.	237.	192.	128.	182.	237.
27	9.	75.	61.	40.	57.	75.
28	20.	168.	136.	91.	129.	168.
29	18.	154.	125.	83.	118.	154.
30	15.	125.	102.	68.	96.	125.
31	162.	1345.	1091.	728.	1031.	1345.
32	140.	1161.	942.	629.	890.	1161.
33	24.	196.	159.	106.	150.	196.
34	29.	237.	192.	128.	182.	237.
35	32.	271.	220.	147.	208.	271.
36	35.	298.	242.	161.	229.	298.
37	8.	75.	61.	40.	57.	75.
38	20.	164.	133.	89.	126.	164.
39	10.	84.	69.	46.	65.	84.
40	14.	118.	96.	64.	90.	118.
41	151.	1249.	1013.	677.	958.	1249.
42	136.	1126.	914.	610.	863.	1126.
43	160.	1325.	1075.	718.	1016.	1325.
44	29.	242.	197.	131.	186.	242.
45	31.	257.	209.	139.	197.	257.
46	36.	300.	244.	163.	230.	300.
47	10.	87.	71.	47.	67.	87.
48	28.	238.	193.	129.	183.	238.
49	12.	105.	85.	57.	81.	105.
50	14.	120.	97.	65.	92.	120.

CELL NO.	1	2	3	4	5	6
51	145.	1201.	975.	651.	921.	1201.
52	141.	1169.	944.	630.	892.	1169.
53	165.	1366.	1108.	740.	1048.	1366.
54	31.	257.	209.	139.	197.	257.
55	48.	403.	327.	218.	309.	403.
56	51.	427.	347.	231.	328.	427.
57	26.	212.	172.	115.	163.	212.
58	37.	310.	251.	168.	237.	310.
59	8.	73.	59.	39.	56.	73.
60	13.	108.	87.	59.	82.	108.
61	141.	1173.	951.	635.	899.	1173.
62	157.	1300.	1055.	704.	997.	1300.
63	174.	1436.	1165.	778.	1101.	1436.
64	28.	234.	190.	127.	179.	234.
65	52.	432.	351.	234.	332.	432.
66	29.	244.	198.	132.	187.	244.
67	49.	409.	332.	221.	313.	409.
68	35.	294.	238.	159.	225.	294.
69	30.	254.	206.	137.	194.	254.
70	5.	48.	39.	25.	36.	48.
71	8.	65.	53.	36.	50.	65.
72	159.	1314.	1066.	712.	1007.	1314.
73	86.	718.	582.	389.	550.	718.
74	30.	250.	203.	135.	191.	250.
75	28.	232.	188.	125.	178.	232.
76	29.	239.	194.	129.	183.	239.
77	48.	398.	323.	215.	305.	398.
78	28.	239.	194.	129.	183.	239.
79	29.	247.	201.	134.	[illegible]	247.
80	14.	115.	93.	62.	88.	115.
81	0.	0.	0.	0.	0.	0.
82	128.	1063.	862.	576.	815.	1063.
83	65.	537.	436.	291.	412.	537.
84	23.	184.	149.	99.	141.	184.
85	36.	300.	243.	162.	230.	300.
86	42.	354.	287.	192.	272.	354.
87	39.	327.	266.	177.	251.	327.
88	29.	246.	199.	133.	189.	246.
89	30.	248.	201.	135.	190.	248.
90	30.	246.	200.	133.	189.	246.
91	0.	0.	0.	0.	0.	0.
92	64.	54.	436.	291.	412.	54.
93	64.	532.	432.	288.	408.	532.
94	30.	246.	199.	133.	188.	246.
95	19.	159.	129.	86.	122.	159.
96	25.	204.	165.	110.	156.	204.
97	29.	246.	199.	133.	188.	246.
98	29.	246.	200.	133.	189.	246.
99	29.	245.	199.	133.	188.	245.
100	33.	271.	220.	147.	208.	271.

6.2 Vehicle Speeds, Intersection Delay, Stopped Separation Distance

Vehicular speeds are extrapolated from Table 4.5 of Reference 13. Values used are shown in Table 11.

TABLE 11

AVERAGE VEHICLE SPEED

Time Interval	$\bar{V}$ (average vehicular speed, including delays) (m/sec)
1	8.06
2	3.34
3	4.05
4	3.62
5	3.83
6	3.34

In addition to average overall speed, the average speed while the vehicle is moving (cruising speed) is also needed. Several factors must be considered before a reasonable calculation for cruising speed may be made. In particular, a value must be obtained for the fraction of intersections at which a vehicle stops while traveling within a cell (ξ). Values for ξ, dependent on time of day, are shown in Table 12.

*Values were estimated using existing information on vehicular speeds and signal characteristics.

TABLE 12

FRACTION OF INTERSECTIONS AT WHICH VEHICLE MUST STOP

Time Interval	ξ (fraction of intersections at which vehicle is required to stop)
1	0
2	1
3	0.5
4	0.75
5	0.5
6	1

Also required is the average length of time a vehicle is delayed by stopping at an intersection (Ω). The value assumed for Ω is 25 seconds.* Note that this does not account for multiple delays at the same intersection resulting from extremely congested conditions. That factor is partially absorbed in the average speed calculation.

A third such intersection-related parameter is the distance between vehicles stopped at an intersection. Experience indicates a wide variation in values for this distance. As a first approximation, a value of 1 meter is used as an input parameter.**

*Albuquerque, New Mexico traffic engineers indicated that this was a reasonable value for the average duration of an urban red light.

**Information from Albuquerque, New Mexico traffic engineers and observations of local patterns were the basis for this assumption.

The final piece of information needed to calculate the cruising speed is the actual distance a vehicle travels in a cell. METRAN assumes a limited number of allowable paths through the cell with a maximum possible distance traveled of 1.414 km (i.e., a diagonal path across the cell; see Section 7). With this information, cruising speed may be obtained with the expression:

$$V_c = \frac{L}{\frac{L}{\bar{V}} - \xi\Omega} , \qquad (4)$$

where L = distance traveled in the cell (m).

TABLE 13

CRUISING SPEEDS

Time Interval	V_c (m/sec)
1	8.06
2	3.56
3	4.19
4	3.81
5	3.97
6	3.56

6.3 Pedestrian Speed

Pedestrians also travel at varying speeds. Information is readily available for varying degrees of pedestrian congestion[13] If these various degrees of congestion are coupled with pedestrian patterns and time of day, the values obtained are:

TABLE 14

PEDESTRIAN SPEEDS

Time Interval	v_p (pedestrian speed in m/sec)
1	2.50
2	1.79
3	1.56
4	1.30
5	1.56
6	1.79

6.4 Number of People per Vehicle

Calculation of people per vehicle (PPV) uses data from Reference 4 which indicate the relationship between total person-miles of travel by autos (including trucks and taxis) and total person-miles of travel for buses on an hourly basis for midtown Manhattan. Person-miles of travel are converted to vehicle-miles of travel by dividing by the vehicle occupancies listed in Table 15.

TABLE 15

VEHICLE OCCUPANCIES

Vehicle Type	Occupancy
Auto	1.5
Bus	
Rush hour	77
Off-peak hours	43
Nighttime	24

Ratios of cars to buses for each time interval are then calculated by dividing the vehicle-miles for cars by the vehicle-miles for buses. (This assumes that a vehicle-mile for a bus is equivalent to the vehicle-mile for an auto.) Values thus obtained are given in Table 16.

TABLE 16

RATIOS OF NUMEER OF CARS TO NUMBER OF BUSES

Time Span	Cars/Bus
1	50.0
2	69.4
3	41.8
4	88.8
5	43.8
6	60.6

(It is not necessary to discriminate between trucks and cars at this point since the occupancies are the same for both.) From these ratios, it is possible to calculate average people per vehicle by summing the percentage of each vehicle type times its occupancy. Results are listed in Table 17.

TABLE 17

PEOPLE PER VEHICLE

Time Span	% Cars	Car Occupancy	% Buses	Bus Occupancy	PPV
1	98.04	1.5	1.96	24	1.95
2	98.58	1.5	1.42	77	2.57
3	97.66	1.5	2.34	43	2.48
4	98.89	1.5	1.11	77	2.33
5	97.77	1.5	2.23	43	2.43
6	98.38	1.5	1.62	77	2.73

6.5 Vehicle Length

Standard design vehicle lengths are available in Reference 4. Of interest are the values for trucks, autos and buses. These values are shown in Table 18.

TABLE 18

STANDARD DESIGN VEHICLE LENGTHS

	Standard Design Vehicle Length (m)
Auto	5.79
Truck	9.14
Bus	12.19

Reference 4 also indicates that 15% of all vehicle trips are by truck. Separating the truck fraction from the total vehicles and from the cars per bus, the distributions of vehicles calculated for each time span are summarized in Table 19.

TABLE 19

DISTRIBUTION OF VEHICLE TRAVEL

Time Span	% Autos	% Trucks	% Buses
1	83.04	15	1.96
2	83.58	15	1.42
3	82.66	15	2.34
4	83.89	15	1.11
5	82.77	15	2.23
6	83.38	15	1.62

Multiplying each percentage by the appropriate length then summing gives an average vehicle length for each time span. Time variation is very small, with an average of 6.4 m and a range of 6.36 m to 6.45 m. The average value of 6.4 m is used in the model.

6.6 Vehicle Separation Distance

Values for separation distance can be obtained both for avenues and streets in Manhattan[13]. Table 4.6 of Reference 13 indicates values for vehicles/m/hr and space in square meters for maximum and comfortable flow for streets and avenues. Vehicles/m/hr is converted to vehicles/hr by multiplying by the lane width of 3.66 m. Space in m^2 is converted to distance per vehicle by dividing by the lane width of 3.66 meters. Since the distance per vehicle includes the vehicle length, this value is subtracted to give a separation distance. Values are included in Table 20.

TABLE 20

METHOD OF CALCULATION OF MOVING VEHICLE SEPARATION DISTANCE

Character of Flow	Streets: Vehicles per Hour	Streets: Effective Length (meters)	Streets: Separation Distance (meters)	Avenues: Vehicles per Hour	Avenues: Effective Length (meters)	Avenues: Separation Distance (meters)
Comfortable Flow	275	69.7	63.3	359	84.7	78.3
Maximum Flow	432	26.0	19.6	564	31.4	25.0

Mean values for comfortable flow and maximum flow (averaging values for streets and avenues) are:

	Vehicles per Hour	Separation Distance (meters)
Comfortable Flow	317	70.8
Maximum Flow	498	22.3

Values for separation distance and vehicles per hour are plotted in Figure 2.

The solid line in Figure 2 stands for the average values of separation distance and vehicles per hour (vph). The curve can be approximated by a straight line with the understanding that this approach may be invalid for extreme values. The dashed lines represent actual data points for avenues and streets. The y-intercept is about 153 meters and the maximum vehicle flow is approximately 575 vph. Values for separation distance may be determined from the assumption of a linear relationship and use of the straight line equation $y = -2.59x + 153$. For vehicle flows greater than 575 per hour, a minimum value of separation distance for each time span is assumed. These minimum values are shown in Table 21.

TABLE 21

VALUES FOR MINIMUM MOVING VEHICLE SEPARATION DISTANCE

Time Span	Minimum Separation Distance (m)
1	1.45
2	.57
3	.71
4	.62
5	.67
6	.57

All values for calculated vehicle separation distance are included in Table 22.

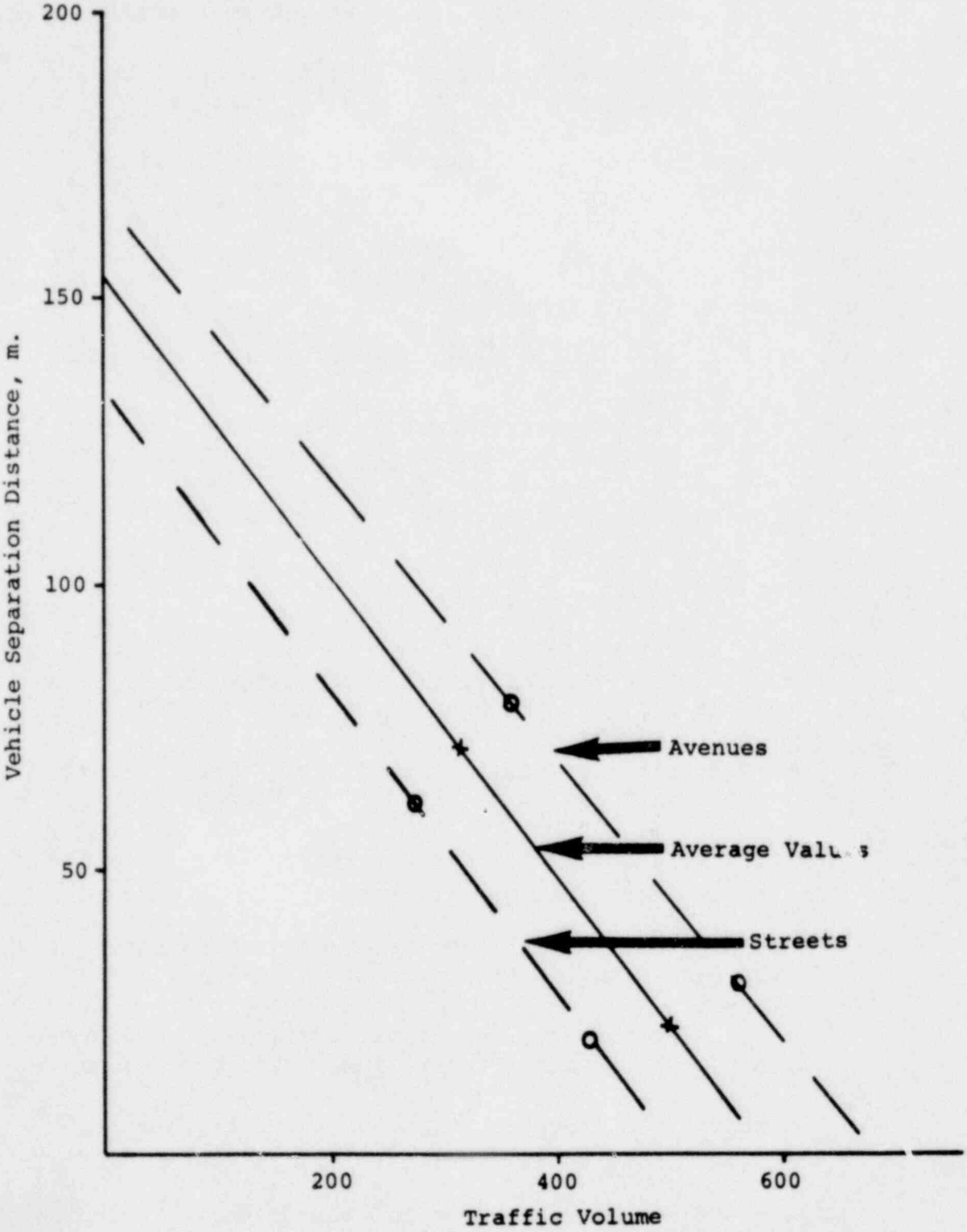


Figure 2. Vehicle Separation Distances vs. Traffic Count

TABLE 22
VEHICLE SEPARATION DISTANCE WHILE MOVING(METERS)
T-I-M-E S-P-A-N

CELL NO.	1	2	3	4	5	6
1	143.10	71.40	87.00	109.00	90.60	71.40
2	147.60	120.60	126.60	135.40	128.10	120.60
3	142.60	66.80	83.10	106.40	87.00	66.80
4	0.00	0.00	0.00	0.00	0.00	0.00
5	150.20	128.10	132.80	139.50	134.10	128.10
6	149.90	126.30	131.20	138.50	132.50	126.30
7	146.50	99.40	109.50	124.00	111.80	99.40
8	142.60	67.30	83.60	106.60	87.20	67.30
9	149.10	119.90	126.10	153.10	127.60	119.90
10	149.60	124.50	130.00	137.70	131.20	124.50
11	143.20	71.40	86.70	109.00	90.30	71.40
12	150.40	131.00	134.40	141.10	135.40	131.00
13	145.00	87.00	99.40	117.30	102.59	87.00
14	151.20	139.50	142.10	145.80	142.60	139.50
15	149.90	126.80	131.80	138.80	133.10	126.80
16	149.90	126.10	131.20	138.30	132.50	126.10
17	150.20	129.40	133.80	140.30	134.90	129.40
18	142.60	67.30	83.60	106.60	97.20	67.30
19	148.60	116.00	123.00	133.10	124.80	116.00
20	148.30	113.10	120.60	131.50	122.40	113.10
21	142.90	71.40	87.00	109.00	90.60	71.40
22	150.40	131.00	134.40	141.10	135.10	131.00
23	145.00	87.20	99.70	117.30	102.50	87.20
24	145.20	89.00	101.20	118.60	104.10	89.00
25	143.70	75.80	90.30	111.30	93.70	75.80
26	145.80	91.60	103.30	119.90	105.90	91.60
27	150.70	133.60	137.20	142.60	138.20	133.60
28	147.80	109.50	117.80	129.40	119.60	109.50
29	148.30	113.10	120.60	131.50	122.40	113.10
30	149.10	120.60	126.60	135.40	128.10	120.60
31	111.00	.57	.71	.62	.67	.57
32	116.70	.57	.71	.62	.67	.57
33	146.80	102.20	111.80	125.60	114.20	102.20
34	145.50	91.60	103.30	119.90	105.90	91.60
35	144.70	82.80	96.00	114.90	99.10	82.80
36	143.90	75.80	90.30	111.30	93.70	75.80
37	150.90	133.60	137.20	142.60	138.20	133.60
38	147.80	110.50	118.60	130.00	120.40	110.50
39	150.40	131.20	135.10	141.10	136.20	131.20
40	149.30	122.40	128.10	136.40	129.70	122.40
41	113.90	.57	.71	.62	.67	.57
42	117.80	.57	.71	.62	.67	.57
43	111.60	.57	.71	.62	.67	.57
44	145.50	90.30	102.00	119.10	104.80	90.30
45	145.00	86.40	98.90	117.00	102.00	86.40
46	143.70	75.30	89.80	110.80	93.40	75.30
47	150.40	130.50	134.60	140.80	135.70	130.50
48	145.80	91.40	103.00	119.60	105.60	91.40
49	149.90	125.80	131.00	138.20	132.00	125.80
50	149.30	121.90	127.90	136.20	129.20	121.90

CELL NO.	1	2	3	4	5	6
51	115.50	.57	.71	.62	.67	.57
52	116.50	.57	.71	.62	.67	.57
53	110.30	.57	.71	.62	.67	.57
54	145.00	86.40	98.90	117.00	102.00	86.40
55	140.60	48.60	68.30	96.50	73.00	48.60
56	139.80	42.40	63.10	93.20	68.10	42.40
57	146.30	98.10	108.50	123.20	110.00	98.10
58	143.40	72.70	88.00	109.50	91.60	72.70
59	150.90	134.10	137.70	142.90	138.50	134.10
60	149.60	125.00	130.50	137.70	131.80	125.00
61	116.50	.57	.71	.62	.67	.57
62	112.30	.57	.71	.62	.67	.57
63	107.90	.57	.71	.62	.67	.57
64	145.80	92.40	103.80	120.10	106.60	92.40
65	139.50	41.10	62.10	92.40	67.00	41.10
66	145.50	89.80	101.70	118.80	104.60	89.80
67	140.30	47.10	67.00	95.80	71.90	47.10
68	143.90	76.90	91.40	111.80	94.70	76.90
69	145.20	87.20	99.70	117.50	102.80	87.20
70	151.70	140.60	142.90	146.30	143.70	140.60
71	150.90	136.20	139.30	143.70	140.10	136.20
72	111.80	.57	.71	.62	.67	.57
73	130.70	.57	2.26	52.30	10.60	.57
74	145.20	88.30	100.40	118.00	103.50	88.30
75	145.80	92.90	104.30	120.60	106.90	92.90
76	145.50	91.10	102.80	119.60	105.60	91.10
77	140.60	49.90	69.30	97.30	74.00	49.90
78	145.80	91.10	102.80	119.60	105.60	91.10
79	145.50	89.00	100.90	118.30	103.80	89.00
80	149.30	123.20	128.90	136.90	130.20	123.20
81	.00	0.00	0.00	0.00	0.00	0.00
82	119.90	.57	.71	4.90	.67	.57
83	136.20	13.90	40.10	77.60	46.30	13.90
84	147.00	105.30	114.40	127.40	116.50	105.30
85	143.70	75.30	90.10	111.00	93.40	75.30
86	142.10	61.30	78.70	103.30	82.60	61.30
87	142.90	68.30	84.10	107.20	88.00	68.30
88	145.50	89.30	101.50	118.60	104.10	89.30
89	145.20	88.80	100.90	118.00	103.80	88.80
90	145.20	89.30	101.20	118.60	104.10	89.30
91	.00	0.00	0.00	0.00	0.00	0.00
92	136.40	139.00	40.10	77.60	46.30	139.00
93	136.40	15.20	41.10	78.40	47.30	15.20
94	145.20	89.30	101.50	118.60	104.30	89.30
95	148.10	111.80	119.60	130.70	121.40	111.80
96	146.50	100.20	110.30	124.50	112.60	100.20
97	145.50	89.30	101.50	118.60	104.30	89.30
98	145.50	89.30	101.20	118.60	104.10	89.30
99	145.50	89.60	101.50	118.60	104.30	89.60
100	144.50	82.80	96.00	114.90	99.10	82.80

6.7 Freeway Traffic Parameters

Freeway traffic parameters include speeds, separation distances, traffic counts, freeway width (center-line to center-line), lane width, and number of lanes per direction.

6.7.1 Freeway Speeds

Information on freeway speeds was obtained from Reference 13, Table 4.6. Values for average speed as a function of time are shown in Table 23.

TABLE 23

FREEWAY SPEEDS

Time Interval	V_f (Freeway Speed) (m/sec)
1	24.4
2	8.9
3	9.7
4	9.7
5	9.7
6	8.9*

*It is obvious that lower values can occur during periods of heavy vehicular congestion.

6.7.2 Miscellaneous Freeway Parameters*

Values assumed for other parameters are listed below:

1) L_f' -- number of freeway lanes per side = 3

2) Lane Width = 3.7 meters

3) Center-line to center-line freeway width:

Median width = 3.1 meters

Lane width = 3.7 meters

w_f = 14.05 meters (1.5 lanes on each side and median)

*Information on all of these was obtained through private communications with persons involved in freeway planning in the New York City area.

4) d_{1f} -- freeway vehicle separations for moving vehicles

TABLE 24

FREEWAY VEHICLE SEPARATIONS

Time Interval	d_{1f} (m)
1	61.
2	3.05
3	18.3
4	18.3
5	18.3
6	3.05

5) N_f -- freeway traffic counts.

TABLE 25

FREEWAY COUNTS IN VEHICLES PER HOUR

Time Interval	N_f (vehicles per hour)
1	3000
2	5400
3	4000
4	4700
5	4000
6	5400

6.8 Rail Parameters*

*Information on all of these was obtained through private communications with persons in the rail transit industry in the New York City area.

6.8.1 Population Densities in Terminal Areas

Information on mass transit characteristics indicates that approximately 70,000 persons use the major urban rail facility in New York during rush hours and that, in addition, there are approximately 20,000 off-peak users of the facility. The major rail transit facility (Grand Central Station) in the study area occupies approximately 0.026 km^2 (measured from maps in Reference 2). Values for people per square kilometer for each time span are obtained by apportioning the off-peak travelers as indicated in Table 26. Converting to hourly values, and presuming a ten minute stay within the area, the effective number of people in the rail transit area at any time within the interval can be calculated.

TABLE 26

POPULATION DENSITIES FOR RAIL TRANSIT FACILITIES

Time Span	No. People for Total Span	Totals for Span (per km^2)	Totals/km^2/hr	Totals/km^2 at any time (assuming 10 min. visit)
1	2000	78,431	6039	1006
2	70000	2,745,098	2.74×10^6	4.57×10^5
3	5000	196,078	56039	9340
4	8000	313,725	209137	34856
5	5000	196,078	56039	9340
6	70000	2,745,098	1.83×10^6	3.05×10^5

6.8.2 Miscellaneous Rail Parameters

Other parameter values are listed below:

1) Length of time a train remains in terminal area (ΔT_{depot})

TABLE 27

ΔT_{depot} FOR TRAINS

Time Interval	ΔT_{depot} (minutes)
1	120
2	10
3	120
4	30
5	120
6	10

2) Minimum exposure radius r_3 = 2.4 meters

3) Maximum exposure radius r_4 = 6.1 meters

4) Distance between passing trains r_5 = 6.1 meters

5) Width of right-of-way (outside terminal area) RW = 9.14 meters

6) Average train speed (within terminal area) v_r = 6.67 m/sec

7) Train traffic count (N_T)

TABLE 28

TRAIN TRAFFIC COUNTS

Time Interval	N_T (two-way) (per hour)
1	9
2	108
3	9
4	36
5	9
6	108

8) Persons per train (PPT).

TABLE 29

PEOPLE PER TRAIN

Time Interval	PPT*
1	96
2	960
3	480
4	480
5	480
6	960

*Values are obtained assuming occupancies of 10% of seating capacity at night, 50% at off-peak hours and 100% at peak times. An average train has eight cars with a seating capacity per car of 120.

6.9 Air Transport Parameters*

La Guardia Airport is the only airport facility in the study area. No cargo terminal exists at this facility, so values for $\Delta T_{c\ term}$ and $PD_{c\ term}$ are set to zero. Other information which proved useful in its original form included:

1) Average time a passenger aircraft remains in the terminal area: $\Delta T_{p\ term}$ = 55 minutes

2) Minimum exposure radius r_6 = 121.9 meters (distance of closest approach for occupants of the terminal before boarding)

3) Maximum exposure radius r_7 = 243.8 meters (approximate maximum distance from aircraft for terminal occupants before boarding).

*Information on these matters was obtained through private communication with air transit experts in the New York City area.

6.9.1 Air Terminal Population Densities

Air terminal population density information is available on an hourly basis and was converted to the time-span basis discussed earlier. These data consider the population to be only in the passenger waiting areas of the terminal building and not in the areas restricted to employees only. It was determined, using a square counting technique, that the terminal area of interest is 0.043 km^2 (Ref. 2). An approximate length of stay of 45 minutes is assumed for persons in the air terminal. The average population densities (including passengers, employees and visitors) by time interval are shown in Table 30.

TABLE 30

AIR TERMINAL POPULATION DENSITIES

Time Interval	Persons/ Hr	Persons/ Hr/km^2	Persons/ km^2
1	1267	29465	39287
2	1610	37442	49923
3	2136	49674	66232
4	2530	58837	78449
5	3200	74419	99225
6	3634	84512	112683

6.10 Water Transport Parameters*

The last of the transport modes to be considered is water transport. Parameters of interest are the following

*Information on shipping data was obtained from Task Group member William Luch and dock officials in the New York City area.

1) ΔT_{dock} -- time spent at dock in hours (for regular shipments)

2) PD_{dock} -- population densities at the dock per km^2 by time interval

3) Minimum and maximum exposure radii.

For containerized shipping (the currently preferred method for transoceanic shipment) a vessel will spend from 24 to 30 hours in port, depending on its size. The minimum exposure radius is on the order of 40 ft (12.2 m) and the maximum exposure radius is on the order of 300 ft (91.4 m). Population density at the cargo docks is about 7000 for the entire area at any time. The major facilities for cargo shippers in the New York City area are at Port Elizabeth, NJ. For this study $PD_{dock} = 0$ for the grid since all water transport is assumed to pass through without stopping.

7. Shipment Information

7.1 Introduction

The transportation of radioactive materials into, around, and through a major urban area involves such a diversity of materials, package types, quantities, package radiation levels, and transport modes, that detailed consideration of every shipment is impractical. Therefore, in order to realistically assess the radiological risk associated with the transportation of radioactive materials in urban areas, it is necessary to select a finite number of shipment types which predominate as radiological risks.

The shipment model used in this document is similar to that used in Reference 1, and is based on the same shipper survey.[14] This discussion outlines the basic mechanics used to reduce the overall survey data to a workable set of New York City "standard shipments."

In the 1975 shippers' survey[14] certain shippers completed "detailed questionnaires" while others completed "summary questionnaires." The detailed questionnaires requested information based upon actual shipping records, while data requested by the summary questionnaires were based upon shipper estimates. Most "major shippers," i.e., those known to ship large numbers of packages annually, and all special nuclear material licensees completed detailed questionnaires, although a few were missed and sent only summary questionnaires. Summary questionnaires sent to a cross-section of licensees were intended to represent the entire licensee population for sampling purposes. Thus, the summary questionnaire data base was divided into two separate groups: one for minor shippers and the other for apparent major shippers. Therefore, three data bases exist: one from the detailed questionnaires, one from the summary questionnaires completed by minor shippers, and one from the summary questionnaires completed by apparent major shippers. Each of these data bases was extrapolated differently to account for the entire shipper population. The set of standard shipments upon which this risk assessment is based was determined from these three data bases.

Each standard shipment is specified by the isotope or material being shipped, the package type, the number of packages shipped per year, the average number of packages per shipment, the average quantity of material per package, the average transport index (TI) per package, the transport modes, and the specific urban route followed.

The final standard shipments model uses a subset of the data in a shipments data base available at Sandia Laboratories, Albuquerque, which is the result of merging data from Reference 14, with a Geographic Data File.[15] In addition to information on shipment characteristics, Reference 14 contains information on shippers' Zip Codes, and shipment destinations (by city and state). Thus, information on shippers is available in a different form from information on receivers.

The Zip Code data from Reference 14 were checked against a file of the latitude and longitude of Zip Codes found in Reference 15. Government organizations whose Zip Codes appeared in Reference 14, but not in the Geographic Data Base, were assigned the latitude and longitude for downtown Washington.

A second file was prepared from Reference 15 with all cities within each state arranged alphabetically. About one-third of the city-state pairs listed in Reference 14 was not in the Geographic Data Base. The observed errors were of three types:

1. Typographic or transcription errors, i.e.,

   BIEMINGHAM, AL
BIRHAMGTON, AL
BIRMHINGHA, AL
BIRMINGHAN, AL
BIRMINSHAM, AL
BIRMINGHAM, AK

   all thought to be BIRMINGHAM, AL.

2. An abbreviation, shortened name or familiar name used in place of a given name, i.e.,

   LA, CA

   thought to be LOS ANGELES, CA (maximum city field is ten characters)

   LASL, NM

   thought to be LOS ALAMOS, NM

   TRAVIS, CA
TRAVIS AF, CA
AFB TRAVER, CA
TRAVIS AFB, CA

   all thought to be TRAVIS AIR FORCE BASE, CA

3. Unresolved, i.e.,

   MIC RIDER, CT

   ROSIN, IL

   (blank), CA or most other state codes

Of the approximately 26,000 city-state pairs in the Reference 14 data, 3600 were unique. After consulting the Geographic Data Base, the Zip Code directory, and a geographic place name dictionary, fewer than 0.1% of the names remained unresolved. Most of the unresolved names represented only one package or shipment per year (a small fraction of the total number of packages in the data base).

A latitude and longitude were found for each corrected city-state pair in the Geographic Data Base. Note that all shipments destined for a city can be found at the latitude and longitude of the city center, although more precise ultimate destinations may be inferred from the isotope and quantity shipped.

Knowledge of the latitude and longitude of both the origin and destination allowed choice of a subset of data which fits any one (or all) of the following criteria:

1) The shipment origin is in the vicinity of a given latitude and longitude;
2) The shipment destination is in the vicinity of a given latitude and longitude;
3) An imaginary line joining the origin and destination passes through the vicinity of a given latitude and longitude.

The expression "vicinity of a given latitude and longitude" is used to caution the potential user. The program assumes that the latitude and longitude are at the center of a circle of radius R measured in degrees. It further assumes that the origin and destination are on this planar grid. The distance on the earth's surface represented by one degree of latitude is independent of a given latitude. A longitude degree represents a distance on the earth's surface that varies with latitude. Hence, the "vicinity" described is more elliptical than circular. (See Figure 3.)

For the New York City study area, concentric circles were drawn centered on the 100 km^2 grid with radii of 5 km and 7 km as measured by latitude or longitude, i.e.; the circles inscribe an area of a certain number of degrees (equivalent to 5 km or 7 km) which will differ if the value is for longitude or for latitude. For longitude measurements:

5 km = 0.0214°

7 km = 0.0296°, and

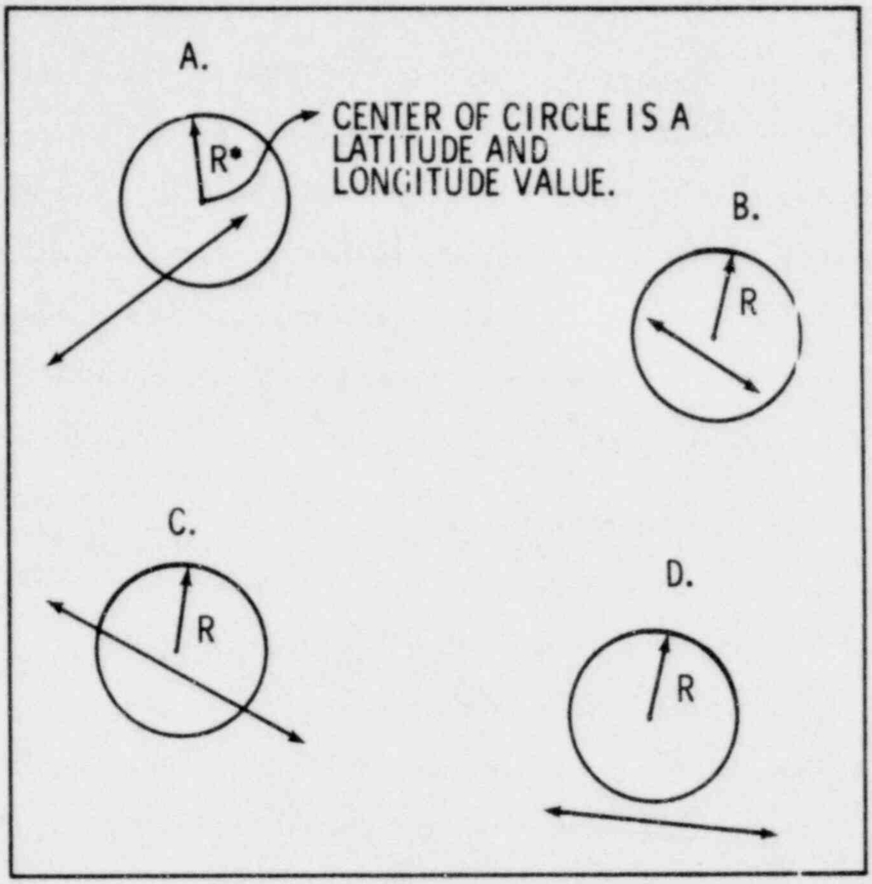
for latitude measurements:

5 km = 0.0133°

7 km = 0.0186°.

The data base was accessed to give shipping information within these circles.

Using this approach, all shipments, but one, had neither origin nor destination within the grid. Since this was not realistic but simply an artifact of the data base, a second approach was devised. In this instance, the center of the 7 km circle was placed at the geographical center of New York City. This approach provided much information on shipments with origins and destinations within this circle. (This approach is more consistent with information actually stored within the Geographic Data Base.) Although the circle circumscribing the geographic city center does not intersect the grid area, the types of shipments reaching or originating within this circle are presumed to be typical for this study area. In preparing



- R IS THE RADIUS OF THE CIRLCE WITHIN WHICH SHIPMENT INFORMATION IS REQUESTED.

TYPES OF INFORMATION WHICH CAN BE ACQUIRED.

A. EITHER ORIGIN OR DESTINATION IS WITHIN CIRCLE.

B. BOTH ORIGIN AND DESTINATION ARE WITHIN CIRCLE.

C. NEITHER ORIGIN NOR DESTINATION IS WITHIN CIRCLE BUT PATH BETWEEN PASSES THROUGH CIRCLE.

D. NEITHER ORIGIN NOR DESTINATION IS WITHIN CIRCLE AND PATH BETWEEN EXCLUDES CIRCLE.

Figure 3. Differing Criteria for Shipment Routes Into, Out Of, Through, and In The Vicinity of a Given Latitude and Longitude

routing information, typical routes were designated for each kind of isotope appearing in the output for the city center circle. No attempt was made to determine the fraction of the total shipments in the city center circle which actually applies to the specific study area. Shipments included in the grid-centered circle are also included and are routed as through shipments, i.e., those which pass through without stopping.

7.2 Development of a Standard Shipments Model

Once the shipment data base had been reduced so that only New York City shipments were included, it was necessary to reduce the remaining 300,000 shipments to a workable set of "standard shipments" as discussed in Appendix A of Reference 1. This reduction process involved three steps: elimination of shipments, combination of remaining shipments, and calculation of shipment parameters.

7.2.1 Elimination Phase

Six categories of shipments were eliminated from the NYC shipment data base: "limited quantity" shipments, mail shipments, shipments where no mode was specified, government shipments, extremely small shipments and miscellaneous shipments.

Limited quantity shipments have been shown to contribute a negligible amount to the overall radiological impact, under accident and accident-free conditions, even when large numbers of packages are shipped.[1] There were very few limited quantity shipments listed in the NYC data base (2.21% of the total shipments, .0061% of total activity, and 7×10^{-4}% of total TI) and these were not included in the final shipments model.

All mail shipments are required by 39 CFR 123-125 to meet the limited packaging requirement. By ignoring these shipments, another 0.71% of the total shipments, 2.7×10^{-4}% of total activity, and .014% of the total TI are excluded.

Shipments for which no mode was specified accounted for only 0.57% of the total shipments, .08% of the total activity, and .41% of the total TI. Rather than assign these to an arbitrary mode, they were excluded from the standard shipments model.

Since government shipments are outside the scope of this study, they were excluded. They accounted for .0068% of the total shipments, 9.98×10^{-4}% of total activity, and .0014% of total TI.

Certain shipments are small enough to be considered negligible from either an accident or accident-free point of view even though they are not shipped under the limited quantity regulations. Using a criterion of 10^{-4} curies per package for dispersible materials and 10^{-3} curies per package for non-dispersible materials, an additional 2.95% of the total shipments, 2.35% of the activity, and 1.54% of the TI were eliminated.

In summary, 1.9×10^{4} shipments (6.42% of the total) were eliminated from the reduced NYC shipment data base. This accounts for 2.4% of the total activity and 2% of the total TI.

Shipments were subdivided by end-use (i.e., medical, industrial, etc.). Typical routes were then established for each end-use category, e.g., industrial shipments could have an origin or destination within the grid or could be through shipments.* Values for curies per package, packages per year, and TI per package were obtained by averaging over all shipments of each isotope in each end-use category by each mode. Methods for specifying a given route follow.

*Information on shipping routes in the New York City area was made available through Dr. Calvin Brantley of New England Nuclear Corporation. A secondary carrier used by New England Nuclear also supplied transport information from the major airport facilities into New York (specifically to Sloane-Kettering Cancer Research Center) and to Long Island (used as an out-of-grid area destination for some through shipments).

Directions of travel within a cell are restricted to 8 vector directions with either origin or destination at the center of the cell as shown below:

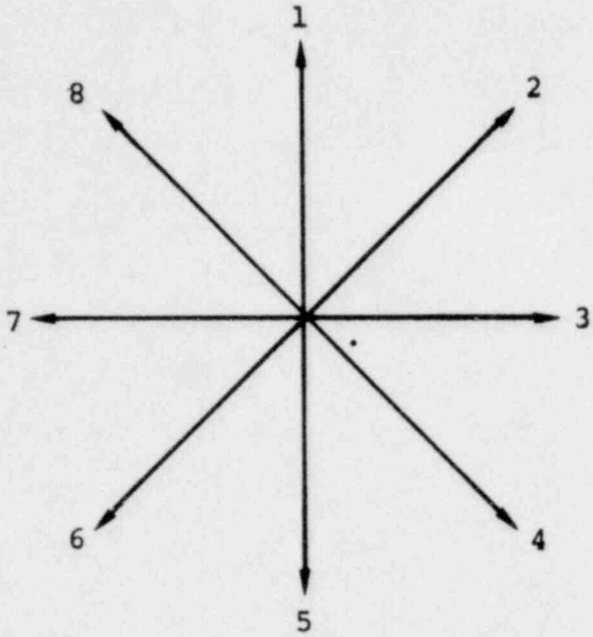


Figure 4. Vector Directions for Travel Within a Cell

The requirement that a route always pass through the center of a cell forces some approximation of the actual route followed.

Possible transport modes include the following:

1) Truck

2) Rail

3) Passenger aircraft

4) Cargo aircraft

5) Watercraft

Roadway types are 1) freeway, 2) two-way streets, 3) one-way streets, and 4) non-road (used for all transport except truck or van). A typical description of a route is as follows:

TABLE 31

TYPICAL ROUTE DESCRIPTION

Cell No.	In Direction	Out Direction	Transport Mode	Road Type
3	5	5	1	2
13	5	5	1	2
23	5	5	1	2
33	5	3	1	2
34	3	3	1	3
35	3	5	1	2
45	5	7	1	2
44	7	Destination	1	2

Although noise abatement ordinances restrict aircraft overflights of the study area, some possible routes for overflights to each major airport facility are included. Through shipment routes on a single transport vehicle, secondary mode transport from an air facility back into the study area, and transfer from one vehicle or mode to another within the study area are allowed to give the model increased flexibility. Quite frequently, shipments are stored for a time before secondary mode transport is begun. The time delay which results is called storage time and is route-dependent.

All shipments and routes are described in Tables 32 - 48, and may be traced using Figure 1.

TABLE NUMBER 32
ROUTE NUMBER 1
END USE: MEDICAL

CELL SEQUENCE	IN DIRECTION	OUT DIRECTION	TRANSPORT MODE	ROAD TYPE
61	3	3	4	0
62	3	3	4	0
63	3	3	4	0
64	3	3	4	0
65	3	3	4	0
66	3	3	4	0
67	3	3	4	0
68	3	3	4	0
69	3	3	4	0
70	3	3	4	0
20	7	5	1	3
30	5	6	1	3
39	6	6	1	3
48	6	7	1	3
47	7	7	1	2
46	7	8	1	2
35	8	7	1	3
34	7	7	1	3
33	7	1	1	2
23	1	0	1	2

ISOTOPE	PACKAGE TYPE	CURIES PER PACKAGE	TRANSPORT INDEX/PKG	PACKAGES PER SHIPMENT	SHIPMENTS PER YEAR	HANDLINGS PER SHIPMENT	STORAGE TIME(HRS)
AU-198	A	1.30E+01	5.0000	1.	641.	4.	0.
CO-60*	A	1.80E+01	9.5610	1.	114.	4.	0.
CR-51	A	5.40E-03	.0400	1.	217.	4.	0.
C-14	A	4.30E-01	5.1630	1.	5060.	4.	0.
HG-197	A	6.50E-02	3.0000	1.	520.	4.	0.
HG-203	DRUM	2.00E-03	4.0000	1.	20.	4.	0.
I-125	A	2.70E-01	.4130	1.	4860.	4.	0.
I-131	A	1.40E-02	6.7130	1.	5290.	4.	0.
MO-99	A	1.20E+00	2.1000	1.	11400.	4.	0.
NA-24	A	6.00E-03	1.9000	1.	484.	4.	0.
P-32	A	2.80E-02	.7500	1.	347.	4.	0.
XE-133	A	2.80E+01	6.3310	1.	1680.	4.	0.

* INDICATES NONDISPERSIBLE SHIPMENTS

TABLE NUMBER 33
ROUTE NUMBER 2
END USE: MEDICAL

CELL SEQUENCE	IN DIRECTION	OUT DIRECTION	TRANSPORT MODE	ROAD TYPE
3	5	5	1	2
13	5	5	1	2
23	5	0	1	2

ISOTOPE	PACKAGE TYPE	CURIES PER PACKAGE	TRANSPORT INDEX/PKG	PACKAGES PER SHIPMENT	SHIPMENTS PER YEAR	HANDLINGS PER SHIPMENT	STORAGE TIME(HRS)
AU-198	A	1.60E-02	1.0000	1.	1040.	1.	0.
CO-57	A	2.60E-05	2.3330	1.	1040.	1.	0.
CO-60*	B	4.70E+03	13.0000	1.	60.	1.	0.
CR-51	A	1.30E-03	2.4000	1.	2600.	1.	0.
C-14	A	7.50E-05	0.0000	1.	1040.	1.	0.
FE-59	A	5.00E-04	.6000	1.	520.	1.	0.
GA-67	A	1.40E-02	.5000	1.	1040.	1.	0.
HG-197	A	2.30E-01	2.5000	1.	1040.	1.	0.
IN-111	A	7.30E-03	0.0000	1.	1560.	1.	0.
IN-114M	A	3.00E-03	4.0000	1.	1210.	1.	0.
I-123	A	2.60E-03	.6000	1.	2600.	1.	0.
I-125	A	4.40E-03	.6320	1.	2490.	1.	0.
I-131	A	8.90E-03	5.8750	1.	18100.	1.	0.
I-131*	A	2.60E-03	7.8040	1.	6240.	1.	0.
MO-99	A	1.00E+00	2.4000	1.	121.	1.	0.
P-32	A	4.30E-03	2.2860	1.	3640.	1.	0.
TC-99M	A	9.70E-02	3.1460	1.	53600.	1.	0.
XE-133	A	1.40E-01	.6250	1.	1160.	1.	0.

* INDICATES NONDISPERSIBLE SHIPMENTS

TABLE NUMBER 34
ROUTE NUMBER 3
END USE: MEDICAL

CELL SEQUENCE	IN DIRECTION	OUT DIRECTION	TRANSPORT MODE	ROAD TYPE
61	3	3	4	0
62	3	3	4	0
63	3	3	4	0
64	3	3	4	0
65	3	3	4	0
66	3	3	4	0
67	3	3	4	0
68	3	3	4	0
69	3	3	4	0
70	3	3	4	0

ISOTOPE	PACKAGE TYPE	CURIES PER PACKAGE	TRANSPORT INDEX/PKG	PACKAGES PER SHIPMENT	SHIPMENTS PER YEAR	HANDLINGS PER SHIPMENT	STORAGE TIME(HRS)
CO-60*	A	1.50E+00	0.0000	1.	208.	0.	0.
C-14	A	3.70E-03	0.0000	1.	910.	0.	0.
C-14*	A	1.50E-03	0.0000	1.	87.	0.	0.
GA-67	A	1.10E-02	.5500	1.	87.	0.	0.
I-125	A	5.30E-03	.4290	1.	303.	0.	0.
MO-99	A	5.90E-01	0.0000	1.	217.	0.	0.
P-32	A	5.30E-03	.5000	1.	260.	0.	0.

* INDICATES NONDISPERSIBLE SHIPMENTS

TABLE NUMBER 35
ROUTE NUMBER 4
END USE: MEDICAL

CELL SEQUENCE	IN DIRECTION	OUT DIRECTION	TRANSPORT MODE	ROAD TYPE
3	5	5	1	2
13	5	5	1	2
23	5	5	1	2
33	5	3	1	3
34	3	3	1	3
35	3	4	1	2
46	4	2	1	2
47	4	3	1	2
48	3	2	1	3
39	2	2	1	3
30	2	2	1	3

ISOTOPE	PACKAGE TYPE	CURIES PER PACKAGE	TRANSPORT INDEX/PKG	PACKAGES PER SHIPMENT	SHIPMENTS PER YEAR	HANDLINGS PER SHIPMENT	STORAGE TIME(HRS)
AU-198	A	5.10E-02	.1500	1.	1040.	0.	0.
CO-57	A	9.50E-05	0.0000	1.	2080.	0.	0.
CR-51	A	1.00E-04	1.0000	1.	520.	0.	0.
C-14	A	1.00E-04	0.0000	1.	520.	0.	0.
GA-67	A	1.20E-02	1.0000	1.	520.	0.	0.
I-123	A	1.00E-03	.5000	1.	1040.	0.	0.
I-125	A	2.20E-05	.3330	1.	1560.	0.	0.
I-131	A	6.60E-03	6.9000	1.	10400.	0.	0.
I-131*	A	3.00E-03	11.1000	1.	1600.	0.	0.
IN-111	A	9.00E-03	0.0000	1.	1040.	0.	0.
MO-99*	A	8.50E-01	2.3000	1.	1560.	0.	0.
TC-99M	A	3.70E-02	1.9720	1.	16700.	0.	0.
XE-133	A	4.00E-02	0.0000	1.	1040.	0.	0.

* INDICATES NONDISPERSIBLE SHIPMENTS

TABLE NUMBER 36
ROUTE NUMBER 5
END USE: INDUSTRIAL

CELL SEQUENCE	IN DIRECTION	OUT DIRECTION	TRANSPORT MODE	ROAD TYPE
3	5	5	1	2
13	5	5	1	2
23	5	5	1	2
33	5	3	1	2
34	3	3	1	3
35	3	5	1	2
45	5	7	1	2
44	7	0	1	2

ISOTOPE	PACKAGE TYPE	CURIES PER PACKAGE	TRANSPORT INDEX/PKG	PACKAGES PER SHIPMENT	SHIPMENTS PER YEAR	HANDLINGS PER SHIPMENT	STORAGE TIME(HRS)
CO-60*	B	4.70E+03	13.0000	1.	60.	1.	0.
CR-51	A	1.30E-03	2.4000	1.	2600.	1.	0.
EU-152	A	2.00E-03	1.0000	1.	120.	1.	0.
FE-55	A	1.50E-01	0.0000	1.	10.	1.	0.
H-3	A	9.30E-03	.3700	1.	540.	1.	0.
KR-85	A	5.00E-03	1.0000	1.	20.	1.	0.
SE-75	A	5.80E-04	2.3330	1.	1560.	1.	0.
XE-133	A	1.40E-01	.6250	1.	1160.	1.	0.
CS-137*	B	1.00E-04	0.0000	1.	20.	4.	0.

* INDICATES NONDISPERSIBLE SHIPMENTS

TABLE NUMBER 37
ROUTE NUMBER 6
END USE: INDUSTRIAL

CELL SEQUENCE	IN DIRECTION	OUT DIRECTION	TRANSPORT MODE	ROAD TYPE
61	2	2	3	0
52	2	2	3	0
43	2	2	3	0
34	2	2	3	0
25	2	2	3	0
16	2	2	3	0
7	2	2	3	0

ISOTOPE	PACKAGE TYPE	CURIES PER PACKAGE	TRANSPORT INDEX/PKG	PACKAGES PER SHIPMENT	SHIPMENTS PER YEAR	HANDLINGS PER SHIPMENT	STORAGE TIME(HRS)
CA-45	A	5.00E-03	0.0000	1.	43.	0.	12.
CR-51	A	1.00E-02	1.0000	1.	217.	0.	12.
H-3	A	8.10E-03	0.0000	1.	737.	0.	12.
NA-22	A	5.00E-04	2.0000	1.	43.	0.	12.
PO-210	B	3.00E-02	1.0000	1.	20.	0.	12.
S-35	A	1.00E-03	0.0000	1.	43.	0.	12.
XE-127	A	1.20E-02	1.0000	1.	20.	0.	12.
XE-133	A	2.70E-01	0.0000	1.	87.	0.	12.

* INDICATES NONDISPERSIBLE SHIPMENTS

TABLE NUMBER 38
ROUTE NUMBER 7
END USE: INDUSTRIAL

CELL SEQUENCE	IN DIRECTION	OUT DIRECTION	TRANSPORT MODE	ROAD TYPE
61	3	3	4	0
62	3	3	4	0
63	3	3	4	0
64	3	3	4	0
65	3	3	4	0
66	3	3	4	0
67	3	3	4	0
68	3	3	4	0
69	3	3	4	0
70	3	3	4	0
20	7	5	1	3
30	5	6	1	3
39	6	6	1	3
48	6	7	1	3
47	7	7	1	2
46	7	8	1	2
35	8	5	1	2
45	5	7	1	2
44	7	0	1	2

ISOTOPE	PACKAGE TYPE	CURIES PER PACKAGE	TRANSPORT INDEX/PKG	PACKAGES PER SHIPMENT	SHIPMENTS PER YEAR	HANDLINGS PER SHIPMENT	STORAGE TIME(HRS)
AM-241*	A	1.00E-01	.3200	1.	1100.	4.	0.
AM-241*	B	1.30E+01	3.0230	1.	480.	4.	0.
CO-60*	A	1.80E+01	9.5610	1.	114.	4.	0.
CR-51	A	5.40E-03	.0064	1.	217.	4.	0.
H-3	A	1.60E-02	0.0000	1.	3030.	4.	0.
IR-192*	A	8.00E+01	1.9000	1.	520.	4.	0.
IR-192*	B	1.00E+02	1.2000	1.	2630.	4.	0.
KR-85	A	2.50E+00	3.3280	1.	821.	4.	0.
SE-75	A	1.60E-02	4.0000	1.	520.	4.	0.
SR-90*	A	8.50E-02	1.8820	1.	340	4.	0.
S-35	A	4.60E-03	0.0000	1.	607.	4.	0.
XE-133	A	2.80E+01	6.3310	1.	1680.	4.	0.
CS-137	DRUM	1.00E-04	.1000	1.	20.	4.	0.

* INDICATES NONDISPERSIBLE SHIPMENTS

TABLE NUMBER 39
ROUTE NUMBER 8
END USE: INDUSTRIAL

CELL SEQUENCE	IN DIRECTION	OUT DIRECTION	TRANSPORT MODE	ROAD TYPE
3	5	5	1	2
13	5	5	1	2
23	5	5	1	2
33	5	3	1	3
34	3	3	1	3
35	3	4	1	2
46	4	2	1	2
47	4	3	1	2
48	3	2	1	3
39	2	2	1	3
30	2	2	1	3

ISOTOPE	PACKAGE TYPE	CURIES PER PACKAGE	TRANSPORT INDEX/PKG	PACKAGES PER SHIPMENT	SHIPMENTS PER YEAR	HANDLINGS PER SHIPMENT	STORAGE TIME(HRS)
CR-51	A	1.00E-04	1.0000	1.	520.	0.	0.
H-3	A	5.00E-03	0.0000	1.	520.	0.	0.
XE-133	A	4.00E-02	0.0000	1.	1040.	0.	0.

* INDICATES NONDISPERSIBLE SHIPMENTS

TABLE NUMBER 40
ROUTE NUMBER 9
END USE: FUEL CYCLE

CELL SEQUENCE	IN DIRECTION	OUT DIRECTION	TRANSPORT MODE	ROAD TYPE
91	8	1	5	0
81	1	1	5	0
71	1	9	5	0

ISOTOPE	PACKAGE TYPE	CURIES PER PACKAGE	TRANSPORT INDEX/PKG	PACKAGES PER SHIPMENT	SHIPMENTS PER YEAR	HANDLINGS PER SHIPMENT	STORAGE TIME(HRS)
U-235	B	2.00E-03	2.4990	1.	22700.	0.	0.
U-238	B	8.50E-03	2.0000	1.	363.	0.	0.

* INDICATES NONDISPERSIBLE SHIPMENTS

TABLE NUMBER 41
ROUTE NUMBER 10
END USE: INDUSTRIAL

CELL SEQUENCE	IN DIRECTION	OUT DIRECTION	TRANSPORT MODE	ROAD TYPE
61	2	2	3	0
52	2	2	3	0
43	2	2	3	0
34	2	2	3	0
25	2	2	3	0
16	2	2	3	0
7	2	2	3	0
7	5	3	1	3
8	3	2	1	3
9	4	6	1	2
18	6	6	1	2
27	6	6	1	2
36	6	7	1	3
35	7	5	1	2
45	5	7	1	2
44	7	0	1	2

ISOTOPE	PACKAGE TYPE	CURIES PER PACKAGE	TRANSPORT INDEX/PKG	PACKAGES PER SHIPMENT	SHIPMENTS PER YEAR	HANDLINGS PER SHIPMENT	STORAGE TIME(HRS)
AM-241*	A	9.30E-01	0.0000	1.	301.	4.	12.
CF-252*	A	2.70E-02	50.0000	1.	20.	4.	12.
CR-51	A	2.20E-01	10.3000	1.	363.	4.	12.
FE-55	A	2.00E-03	0.0000	1.	10.	1.	0.
H-3	A	1.10E-02	0.0000	1.	2320.	4.	12.
KR-85	A	5.00E-01	1.5710	1.	140.	4.	12.
RA-226	A	2.00E-04	1.0000	1.	121.	4.	12.
SE-75	A	2.50E-04	2.0000	1.	520.	4.	12.
SN-113*	A	2.20E-02	15.0000	1.	484.	4.	12.
SR-89	A	4.50E-02	4.0000	1.	121.	4.	12.
XE-133	A	1.60E+00	1.9850	1.	2410.	4.	12.

* INDICATES NONDISPERSIBLE SHIPMENTS

TABLE NUMBER 42
ROUTE NUMBER 11
END USE: WASTE

CELL SEQUENCE	IN DIRECTION	OUT DIRECTION	TRANSPORT MODE	ROAD TYPE
3	5	5	1	2
13	5	5	1	2
23	5	5	1	2
33	5	3	1	2
34	3	3	1	3
35	3	4	1	2
46	4	2	1	2
47	4	3	1	3
48	3	2	1	3
39	2	2	1	3
30	2	2	1	3

ISOTOPE	PACKAGE TYPE	CURIES PER PACKAGE	TRANSPORT INDEX/PKG	PACKAGES PER SHIPMENT	SHIPMENTS PER YEAR	HANDLINGS PER SHIPMENT	STORAGE TIME(HRS)
WASTE	A	4.20E-06	1.0000	1.	300.	0.	0.

* INDICATES NONDISPERSIBLE SHIPMENTS

TABLE NUMBER 43
ROUTE NUMBER 12
END USE: FUEL CYCLE

CELL SEQUENCE	IN DIRECTION	OUT DIRECTION	TRANSPORT MODE	ROAD TYPE
3	5	5	1	2
13	5	5	1	2
23	5	5	1	2
33	5	3	1	2
34	3	3	1	3
35	3	4	1	2
46	4	2	1	2
47	4	3	1	3
48	3	2	1	3
39	2	2	1	3
30	2	2	1	3

ISOTOPE	PACKAGE TYPE	CURIES PER PACKAGE	TRANSPORT INDEX/PKG	PACKAGES PER SHIPMENT	SHIPMENTS PER YEAR	HANDLINGS PER SHIPMENT	STORAGE TIME(HRS)
U-235	B	3.50E-06	2.5000	1.	90.	0.	0.

* INDICATES NONDISPERSIBLE SHIPMENTS

TABLE NUMBER 44
ROUTE NUMBER 13
END USE: MEDICAL

CELL SEQUENCE	IN DIRECTION	OUT DIRECTION	TRANSPORT MODE	ROAD TYPE
61	2	2	3	0
52	2	2	3	0
43	2	2	3	0
34	2	2	3	0
25	2	2	3	0
16	2	2	3	0
7	2	2	3	0

ISOTOPE	PACKAGE TYPE	CURIES PER PACKAGE	TRANSPORT INDEX/PKG	PACKAGES PER SHIPMENT	SHIPMENTS PER YEAR	HANDLINGS PER SHIPMENT	STORAGE TIME(HRS)
C-14	A	1.50E-03	0.0000	1.	347.	0.	12.
CR-51	A	1.00E-02	1.0000	1.	217.	0.	12.
I-123	A	8.00E-02	5.0000	1.	20.	0.	12.
I-125	A	1.50E-03	0.0000	1.	1470.	0.	12.
MG-28	A	2.20E-04	10.0000	1.	120.	0.	12.
MO-99	A	1.40E+00	2.0000	1.	43.	0.	12.
P-32	A	1.60E-03	.1430	1.	303.	0.	12.
P-33	A	1.00E-02	0.0000	1.	43.	0.	12.
TL-201	A	5.70E-03	1.0000	1.	60.	0.	12.
XE-127	A	1.20E-02	1.0000	1.	20.	0.	12.
XE-133	A	2.70E-01	0.0000	1.	87.	0.	12.

* INDICATES NONDISPERSIBLE SHIPMENTS

TABLE NUMBER 45
ROUTE NUMBER 14
END USE: INDUSTRIAL

CELL SEQUENCE	IN DIRECTION	OUT DIRECTION	TRANSPORT MODE	ROAD TYPE
61	3	3	4	0
62	3	3	4	0
63	3	3	4	0
64	3	3	4	0
65	3	3	4	0
66	3	3	4	0
67	3	3	4	0
68	3	3	4	0
69	3	3	4	0
70	3	3	4	0

ISOTOPE	PACKAGE TYPE	CURIES PER PACKAGE	TRANSPORT INDEX/PKG	PACKAGES PER SHIPMENT	SHIPMENTS PER YEAR	HANDLINGS PER SHIPMENT	STORAGE TIME(HRS)
CO-60*	A	1.50E+00	0.0000	1.	208.	0.	0.
CR-51	A	1.10E-02	1.0000	1.	217.	0.	0.
H-3	A	8.80E-03	0.0000	1.	1910.	0.	0.
IR-192*	A	6.00E+01	10.0000	1.	208.	0.	0.
S-35	A	4.00E-03	0.0000	1.	130.	0.	0.

* INDICATES NONDISPERSIBLE SHIPMENTS

TABLE NUMBER 46
ROUTE NUMBER 15
END USE: MEDICAL

CELL SEQUENCE	IN DIRECTION	OUT DIRECTION	TRANSPORT MODE	ROAD TYPE
61	2	2	3	0
52	2	2	3	0
43	2	2	3	0
34	2	2	3	0
25	2	2	3	0
16	2	2	3	0
7	2	2	3	0
7	5	3	1	3
8	3	2	1	3
9	4	6	1	2
18	6	6	1	2
27	6	6	1	2
36	6	7	1	3
35	7	7	1	3
34	7	7	1	3
33	7	1	1	2
23	1	0	1	2

ISOTOPE	PACKAGE TYPE	CURIES PER PACKAGE	TRANSPORT INDEX/PKG	PACKAGES PER SHIPMENT	SHIPMENTS PER YEAR	HANDLINGS PER SHIPMENT	STORAGE TIME(HRS)
AU-198	A	7.80E-03	2.0000	1.	484.	4.	12.
CO-57	A	6.00E-01	2.6000	1.	242.	4.	12.
CR-51	A	2.20E-01	10.3330	1.	363.	4.	12.
C-14	A	8.00E-05	0.0000	1.	1810.	4.	12.
FE-52	A	2.52E+00	40.0000	1.	40.	4.	12.
HG-203	A	1.00E-02	3.0000	1.	520.	4.	12.
I-125	A	1.90E-03	.0460	1.	15800.	4.	12.
I-131	A	4.00E-02	4.8450	1.	8560.	4.	12.
K-43	A	2.00E-03	4.0000	1.	242.	4.	12.
MG-28	A	5.20E+01	11.1000	1.	460.	4.	12.
MO-99	A	1.30E+00	1.3180	1.	14700.	4.	12.
MO-99	B	9.10E+01	6.2000	1.	484.	4.	12.
P-32	A	1.30E-01	4.3650	1.	2530.	4.	12.
TL-201	A	3.10E-03	4.2500	1.	80.	4.	12.
XE-133	A	1.60E+00	1.9850	1.	2410.	4.	12.

* INDICATES NONDISPERSIBLE SHIPMENTS

TABLE NUMBER 47
ROUTE NUMBER 16
END USE: WASTE

CELL SEQUENCE	IN DIRECTION	OUT DIRECTION	TRANSPORT MODE	ROAD TYPE
3	5	5	1	2
13	5	5	1	2
23	5	5	1	2
33	5	3	1	2
34	3	3	1	3
35	3	4	1	2
46	4	2	1	2
47	4	3	1	3
48	3	2	1	3
39	2	2	1	3
30	2	2	1	3

ISOTOPE	PACKAGE TYPE	CURIES PER PACKAGE	TRANSPORT INDEX/PKG	PACKAGES PER SHIPMENT	SHIPMENTS PER YEAR	HANDLINGS PER SHIPMENT	STORAGE TIME(HRS)
MCP	DRUM	8.40E-05	2.3940	1.	660.	0.	0.

* INDICATES NONDISPERSIBLE SHIPMENTS

TABLE NUMBER 48
ROUTE NUMBER 17
END USE: FUEL CYCLE

CELL SEQUENCE	IN DIRECTION	OUT DIRECTION	TRANSPORT MODE	ROAD TYPE
30	6	6	1	3
39	6	6	1	3
48	6	7	1	3
47	7	7	1	3
46	7	8	1	3
35	8	7	1	3
34	7	7	1	3
33	7	7	1	2
32	7	8	1	2
21	8	1	1	3
11	1	1	1	3
1	1	1	1	3

ISOTOPE	PACKAGE TYPE	CURIES PER PACKAGE	TRANSPORT INDEX/PKG	PACKAGES PER SHIPMENT	SHIPMENTS PER YEAR	HANDLINGS PER SHIPMENT	STORAGE TIME(HRS)
SPF-IN	CASK-1	3.00E+03	0.0000	1.	12.	0.	0.
SPF-EX*	CASK-2	2.17E+05	1.0000	1.	12.	0.	0.

* INDICATES NONDISPERSIBLE SHIPMENTS

8. Accident Rates and Delay Times

8.1 Motor Vehicle

Bureau of Motor Carrier Safety data for 1975[16] for carriers of property in interstate commerce indicate the following breakdown of accident occurrences with time of day (adapted to time spans in this study by assuming uniform distribution of accidents across the 3-hr.-time periods in the original information).

TABLE 49

TIME DISTRIBUTION OF ACCIDENTS

Time Span	Time	% of Overall Accidents
1	1800 - 0700	41.7
2	0700 - 0800	4.1
3	0800 - 1130	18.1
4	1130 - 1300	8.5
5	1300 - 1630	20.1
6	1630 - 1800	7.5

Data for 1974 indicate 3.4×10^6 accidents involving trucks with total vehicular travel amounting to 1.290×10^{12} mi. for the same period. Since many truck accidents do involve other vehicles, total vehicle-miles are used. This gives an overall accident rate of 2.64×10^{-6} truck accidents/mi. Converting to metric units gives 1.58×10^{-6} accidents/km. Discriminating with time span gives:

TABLE 50

TRUCK ACCIDENT RATES BY TIME SPAN

Time Span	Accident Rate/km
1	6.59×10^{-7}
2	6.48×10^{-8}
3	2.86×10^{-7}
4	1.34×10^{-7}
5	3.18×10^{-7}
6	1.19×10^{-7}

The fractional occurrences by accident severity category are taken from average values for property damage accidents in major urban areas* (Philadelphia, San Francisco, Los Angeles; information on New York City was not readily available) and values for injury and fatality accidents. It is assumed that no fatal accidents occur in less than category V severity accidents and that injuries occur predominantly on category II - category IV accidents. A value of 0.714 represents an average value for accidents involving only property damage. The fraction 0.283 is the total for all accidents involving injuries, leaving 0.003 as the fraction of accidents with fatalities. Subdividing the injury and fatality values yields the following table of fractional occurrences:

*Telephone conversations with public information offices of police departments in cities noted above.

TABLE 51

FRACTIONAL OCCURRENCES FOR TRUCK ACCIDENTS

Accident Severity Category	Fractional Occurrences
I	.714
II	.228
III	.044
IV	.010
V	.0021
VI	.00083
VII	6.38×10^{-5}
VIII	1.13×10^{-5}

Tabulation of fractional accident rates by severity category and time span are summarized in Table 52.

TABLE 52

TRUCK ACCIDENT RATES

	Time Span					
Severity	1	2	3	4	5	6
1	4.69E-07	4.46E-08	2.05E-07	9.80E-08	2.23E-07	8.50E-08
2	1.49E-07	1.43E-08	6.60E-08	3.14E-08	7.10E-08	2.71E-08
3	2.89E-08	2.75E-09	1.26E-08	6.05E-09	1.38E-08	5.23E-09
4	6.60E-09	6.00E-10	2.88E-09	1.38E-09	3.13E-09	1.19E-09
5	1.38E-09	1.31E-10	6.04E-10	2.89E-10	6.60E-10	2.49E-10
6	5.45E-10	5.19E-11	2.39E-10	1.14E-10	2.59E-10	9.90E-11
7	4.19E-11	3.99E-12	1.83E-11	8.80E-12	1.99E-11	7.60E-12
8	7.40E-12	7.10E-13	3.25E-12	1.56E-12	3.53E-12	1.34E-12

8.2 Aircraft

For the New York City 100 km^2 study area, 32.84 km^2 are streets, 51.74 km^2 are occupied by buildings, and the remaining 15.42 km^2 are open area (water, parks, etc.). A previous study[1] derated the aircraft accident rates to account for real surface effects as distinguished from unyielding surface accident rates. Since the data in Reference 1 are for the entire nation, and reflect the high frequency of open area, an adaptation of these data to the urban scenario is necessary. Surface type designations from Reference 1 were adapted to the urban scenario, and the probability of occurrence of a particular surface type was multiplied by the appropriate urban area in km^2 (open, streets, buildings). The resulting numbers were then renormalized to yield a set of revised probabilities for the urban area. These values are listed in Table 53.

Using the probability information in Table 53, the severity-dependent aircraft accident occurrence probabilities can be derated as in Appendix H of Reference 1. This derating is required because the urban environment does not in general present as unyielding a target as that used as a basis for the accident rates. If the comparison of urban open space with water/soft soil and urban street/buildings with hard soil/soft rock/hard rock is extended to the values for Young's modulus and Poisson's ratio, then the values for V/V_s can be extracted from Table H-1 of Reference 1 and used directly. If this is done, the values given in Table 54 can be computed.

TABLE 53

FRACTIONAL OCCURRENCES FOR AIRCRAFT ACCIDENTS IN URBAN AREAS

Surface Type	Urban Area Example	Fractional Occurrences in Urban Areas	V/V_s*
Water	Water	0.055	4.48
Yielding surface	Parks, cemeteries, other open space	0.085	7.05
Slightly unyielding surface	Streets, small residential buildings	0.799	2.95**
Moderately unyielding surface	Other buildings	0.051	2.21
Unyielding surface***	Abutments, steel reinforcements	0.01	1.0

*Ratio of impact velocity onto a real surface to the impact velocity for similar damage onto an unyielding surface.

**Arithmetic mean of values for hard soil and soft rock in Reference 1.

***A 1% value for unyielding surface has been added for conservativism as was done in Reference 1.

TABLE 54

DERATING SCHEME FOR AIRCRAFT ACCIDENTS

Accident Severity	Fractional Occurrence Unyielding Surface	Fraction Deleted by Derating	Fraction Unyielding	Fraction Added by Derating					Fractional Occurrence Real Surfaces
				w	ys	sus	mus	total	
VIII	.03	.0297	.0003	0	0	0	0	0	.0003
VII	.04	.0396	.0004	0	0	0	.0015	.0015	.0019
VI	.03	.0297	.0003	0	0	.024	0	.024	.0243
V	.03	.0297	.0003	.0016	0	.031	.002	.035	.0353
IV	.05	.0495	.0005	.0022	.0025	.024	.003	.032	.0325
III	.09	.0891	.0009	.0016	.0034	.024	.0015	.031	.0319
I, II	.73	*	*	.024	.017	.11	.0071	.16	.888

*Categories I and II not derated.

8.3 Rail Transport

Information on rail transport accident rates was taken from Table 5.5 of Reference 1. Values for accident rates to be applied to this study are listed in Table 55.

TABLE 55

FRACTIONAL OCCURRENCES FOR TRAIN ACCIDENTS BY ACCIDENT SEVERITY CATEGORY

Accident Severity Category	Fractional Occurrences*
I	.50
II	.30
III	.18
IV	.018
V	.0018
VI	1.3×10^{-4}
VII	6.0×10^{-5}
VIII	1.0×10^{-5}

*Overall Accident Rate = 0.93×10^{-6} railcar accidents/railcar-kilometer.

8.4 Accident Rates for Water Transport

Accident rates for ship or barge accidents within the study area are identical to those used in Reference 1. Values from Table 57 of Reference 1 which are pertinent to this analysis are given in Table 56.

TABLE 56

ACCIDENT RATES FOR WATER TRANSPORT

Accident Severity Category	Fractional Occurrence*
I	0.897
II	0.0798
III	0.00113
IV	0.0186
V	0.0000052
VI	0.000072
VII	0.000195
VIII	0.000013

*Overall accident rate = $.06 \times 10^{-6}$ accidents/kilometer.

8.5 Delay Time

Accident delay time is defined as the length of time a carrier vehicle (and, therefore, the transported material) does not move following an accident.

Basic information on delay time for various accident situations was obtained from a frequent carrier of radioactive materials in the New York area. Officials there indicated that the time following a minor traffic accident before the vehicle began to move again was from 30 minutes to 4 hours with an average around 2 hours. On the other hand, severe accidents, where the tractor or trailer was incapacitated, could cause delays on the average of 6-8 hours with a maximum of about 24 hours. It was also indicated that geographical location and time of day were not significant factors in these delay times.

The following table indicates the approximated values for delay times:

TABLE 57

ESTIMATED ACCIDENT DELAY TIMES FOR TRUCKS

Severity Class	Estimated Accident Delay Time (hr)
I	0.5
II	1.0
III	2.0
IV	4.0
V	8.0
VI	12.0
VII	18.0
VIII	24.0

The small quantity of data available in NRC and DOT accident records supports the estimates for category II - V accidents. Values may be quite high for more severe accidents but the paucity of available data makes this type of number difficult to obtain. The values in Table 57 are used for all modes under the assumption that the delay time is more dependent on the overall accident severity than on the mode of transport.

9. Dosimetric Information

This section is divided into two subsections. The first subsection discusses the values used for rem-per-curie inhaled for each isotope. The second section discusses miscellaneous additional dosimetric factors.

9.1 Rem-per-Curie Values

The values for rem-per-curie inhaled have been obtained from five main sources. The principal source for the values is the INREM code[17] which provides dose equivalents in units of rem per microcurie for 1 micrometer AMAD (activity mean aerodynamic diameter) particles deposited in the pulmonary portion of the respiratory tract. In several cases, data did not exist within the INREM data file for specific organs or for specific radionuclides. In some of these cases, data from Reference 18 were used. These values are given in the source table as rem-per-curie inhaled for a one micrometer AMAD log-normal particle size distribution. Therefore, in order to make values from that tabulation compatible with those from INREM, each value from Reference 18 was multiplied by 4 to give the corresponding pulmonary deposition value. Where data were not available in either Reference 17 or 18, values from References 19, 20, or 21 were used. Where no values could be found in the literature, rem-per-curie values were computed from the maximum permissible concentration values for chronic exposure for 168 hours/week[22] using the following formula from Reference 1 (Appendix A).

$$D = \frac{10^6 * D_o}{K * BR * MPC_a} * f \qquad (7)$$

where D = dose (rem/curie inhaled)

D_o = allowed organ dose[23]*

K = units conversion factor

BR = breathing rate (assumed to be 20 liters/min)

MPC_a = maximum permissible concentration in air (168 hr/week) (μci/ml)

f = a factor which accounts for the fact that values tabulated in Reference 22 assume various values for respirable fraction

MPC_a values were obtained from Reference 22, and in the absence of specific information, gonad doses were set equal to 1% of total body doses.

Dispersal of a shipment of spent fuel presents a unique problem in that the exposed population may inhale an isotopic mixture. This may also be true of mixtures of plutonium isotopes, etc. In order to address this aspect of the problem, the rem-per-curie values for the various released isotopes were weighted by the curies released from a postulated incident. These values were then combined to give rem-per-curie inhaled values for the release of the postulated mixture of isotopes. Values for all isotopes are given in Table 58.

*12 rem/yr whole body and gonad; 30 rem/yr for skin, thyroid, bone; 15 rem/yr other organs.

TABLE 58

REM-PER-MICROCURIE VALUES USED (a)

Isotope	1-yr Lung(b)	50-yr Lung(b)	1-yr Marrow	50-yr Marrow	50-yr LLI(b)	50-yr Thyroid	50-yr Bone	50-yr Gonads(c)	Primary References
H-3	3.6E-6(d)	6.0E-5	3.6E-6(d)	6.0E-5	6.0E-5	6.0E-5	—	6.0E-7	24
C-14	7.2E-5	.0036	7.2E-5(e)	.0036	.005	.0036	.019	3.6E-5	21,22,23
Na-22	.11(j)	.11	.11(j)	.11	.043	.11	.11	1.1E-3	17,19,21,22
Na-24	.01(j)	.01	.01(j)	.01	.01	.01	.01	1E-4	1
*Mg-28(f)	.017(j)	.017	.0013(j)	.0013	.01	6.8E-4	.008	1.3E-5	18,19
P-32	.12(j)	.12	.05(j)	.05	.054	.17	.37	.017	17,19,21,22
P-33(g)	.076(j)	.076	.03(j)	.03	.034	.11	.24	1.9E-4	17,22
S-35	.008(j)	.008	.009(j)	.009	.004	—	.004	.01	17,19,22
K-43	—	—	.001	.001	—	—	—	1E-5	22
Ca-45	.054(h)	.071	.006(h)	.0079	.05	—	.37	1.8E-4	17,19,22
Cr-51	.015(j)	.015	1.0E-4(j)	1.0E-4	7.1E-4	1.9E-4	—	1.8E-4(k)	17,19,21,22
Fe-52	.021(j)	.021	.051(j)	.051	.061	0.0	.0023	.0056(k)	17,19,22
Fe-55	6.2E-4	.002	5.5E-4	.0018	3.E-4	—	.0014	1.8E-5	17,22
Co-57	.032(j)	.032	9.5E-4(j)	9.5E-4	.003	—	—	1.44E-3(k)	17,19,22
Co-58	.24(j)	.24	.012(j)	.012	.029	.0064	.01	.0055(k)	18,19
Fe-59	.0082	.0083	.02(j)	.02	.024	—	.012	2.2E-3(k)	17,19,21,22
Co-60	1.84	5.2	.084	.23	.076	.176	.2	.148(k)	18,19
Ga-67(l)	4.76E-4(j)	4.76E-4	3.8E-4(j)	3.8E-4	3.8E-4	—	9.51E-4	3.8E-6	19

TABLE 58 - continued

Isotope	1-yr Lung(b)	50-yr Lung(b)	1-yr Marrow	50-yr Marrow	50-yr LLI(b)	50-yr Thyroid	50-yr Bone	50-yr Gonads(c)	Primary References
Se-75	.071(j)	.071	.0046(j)	.0046	.004	--	—	.01	17,19
Kr-85	7.2E-7(j)	7.2E-7	2.4E-6(j)	2.4E-6	.004	7.2E-7	6E-7	6E-3	18,19
Sr-89	.031(j)	.031	.052(j)	.052	.056	.0048	.12	5.2E-4	18
Sr-90	.064	.072	.44	2.92	.064	.011	11.1	.029	18
Y-90	.132(j)	.132	.002(j)	.002	.16	8.4E-5	.004	2E-5	18
Y-91	.8(j)	.8	.037(j)	.037	.2	7.2E-4	.076	3.7E-4	18
Zr-95	.52(j)	.52	.014(j)	.014	.06	.006	.014	1.4E-4	18
Nb-95	.12(j)	.12	.0056(j)	.0056	.028	.0038	.0048	5.6E-5	18
Mo-99	.064(j)	.064	5.2E-4(j)	5.2E-4	.084	6E-4	4.4E-4	8E-7	18,19
Tc-99m	3.56E-4(j)	3.56E-4	4.4E-5(j)	4.4E-5	4.4E-5	1.84E-4	4E-5	1.6E-5(k)	16,19
Ru-103	.22(j)	.22	.0044(j)	.0044	.044	.0026	.0035	4.4E-5	18
Ru-106	10	15.6	.014	.025	.52	.004	.0059	2.5E-4	18
In-111(m)	.031(j)	.031	.0014(j)	.0014	.0071	9.5E-4	.0012	1.4E-5	18
Sn-113	.12(j)	.12	.003(j)	.003	.002	.007	.031	3E-5	20
In-114m	0.1(j)	0.1	.011(j)	.011	.071	.002	.049	1.1E-4	18,22
I-123	--	—	7.E-4(j)	7E-4	—	.02	—	7.E-7	19
I-125	--	—	.002(j)	.002	—	1.2	—	1.1E-4(k)	19
Xe-127(n)	5.8E-6(j)	5.8E-6	2.3E-5(j)	2.3E-5	6.2E-6	6.E-6	5.1E-6	2.3E-7	18
Te-127	.0064(j)	.0064	1.6E-5(j)	1.6E-5	7.8E-4	1.2E-5	2.1E-5	1.9E-4	17,18
Te-127m	.48(j)	.48	.003	.0032	.084	7.6E-4	.008	.014	17,18

TABLE 58 - continued

Isotope	1-yr Lung(b)	50-yr Lung(b)	1-yr Marrow	50-yr Marrow	50-yr LLI(b)	50-yr Thyroid	50-yr Bone	50-yr Gonads(c)	Primary References
Te-129	.0022(j)	.0022	4.4E-6(j)	4.4E-6	2.3E-5	3.2E-6	4.8E-6	6.2E-5	17,18
Te-129m	0.6(j)	0.6	.0033(j)	.0033	.15	.0015	.0056	.022	17,18
I-131	.0096(j)	.0096	7.6E-4(j)	7.6E-4	.0014	4.4	8.4E-4	7.3E-4(k)	18,19
Xe-133	1.6E-6(j)	1.6E-6	6.4E-6(j)	6.4E-6	1.7E-6	1.6E-6	1.4E-6	6.4E-6	18,19
Cs-134	.18	.2	.17	.19	.07	.056	.19	.0019	18
Cs-137	.14	.16	.12	.15	.04	.038	.14	.0015	18
Ce-141	.25(j)	.25	.0144	.037	.06	2.8E-4	.0013	3.7E-4	18
Ce-144	8.4	11.7	.024	5.2	.48	3.4E-4	.04	.052	18
Eu-152	2.9E-4	.0029	3.97E-5	3.97E- 4	.021	—	.48	1.6E-4	17,21,22
Ir-192	.252(j)	.252	.005(j)	.005	.036	—	—	5E-5	17,20
Hg-197	.0019(j)	.0019	6E-4(j)	6E-4	.002	—	—	1.9E-5(k)	17,19,22
Au-198	.0089(j)	.0089	.003(j)	.003	.027	—	—	1.8E-4(k)	17,19,22
Tl-201	4.3E-7(j)	4.3E-7	5.7E-4(j)	5.7E-4	.007	—	2.5E-4	5.7E-6	17,22
Hg-203	.09(j)	.09	.006(j)	.006	.01	—	—	6E-5	17,22
Po-210	32.4(j)	32.4	.4(j)	.4	.043	—	1.8	4E-3	20
Ra-226	97.5(j)	97.5	95(j)	95.	.04	—	404	.95	17,19,22
U-233	1.1(e)	55.3	.026(e)	1.3	.04	—	22.1	.013	17,25
U-238	.94(e)	47.3	.024(e)	1.2	.04	—	20.3	.012	17,25
Pu-238	480	1240	.024	5.2	.052	.0024	3040	.052	18
Pu-241	.26	2.36	2.4E-5	.13	.019	5.6E-7	68	.0013	18

TABLE 58 - continued

Isotope	1-yr Lung(b)	50-yr Lung(b)	1-yr Marrow	50-yr Marrow	50-yr LLI(b)	50-yr Thyroid	50-yr Bone	50-yr Gonads(c)	Primary References
Am-241	520	1280	.029	6.4	.22	.003	3600	.064	18
Cm-242	304	348	.013	.02	.23	23.2			
Cf-252	50(p)	201	11(p)	44	.21	—	.829	.11	20
Spent Fuel (case 1) (q,r)	4.1	6.1	.03	.088	.045	.0058	7.1	4.2E-5	18
Spent Fuel (cases 2,3) (q,r)	2.0	2.9	.032	.062	.025	.008	3.5	2.1E-5	18
Spent Fuel (case 5) (q,r)	4.0	5.8	.036	.091	.044	.008	6.8	4.0E-5	18
SNM(q,r)	3.7	951	.018	4.2	.16	.0018	2461	—	18
Waste (s)	.14	.16	.12	.15	.04	.038	.14	.0015	18
MF + MC (t)	1.84	5.2	.084	.23		.176	.2	.148(k)	18,19

Notes for Table 58

(a) Values describe the dose per microcurie deposited in the pulmonary compartment. Values extracted from Reference 19 are generally for intravenous injection, although they are used as if they were for inhalation.

(b) Values given are the larger of the values specified for a soluble or insoluble specie.

(c) In many cases, gonadal dose values are not specified. In these cases, 1% of the whole-body (marrow) dose was used based on methodology suggested in Reference 22.

(d) Based on the 12-year half-life, it is assumed that 6% of the total ultimate dose is accumulated in 1 year.

(e) Based on the half-life being much greater than 50 years, it is assumed that the dose is accumulated uniformly over the first 50 years.

(f) Mg-28 is approximated by the Sr-91 value since Sr and Mg are similar chemically and since the β and γ energies are comparable (2.67 mev/1.07 mev for Sr-91; 1.836 mev/1.37 for Mg-28). Values for bone doses are taken from Reference 19 using Mg-28 data.

(g) P-33 values are approximated by P-32 values divided by 1.58 to account for the lower photon energy.

(h) Using an effective half-life of 162 days, it is assumed that 75% of the ultimate dose is received in the first year.

(i) Deleted.

(j) Because of the short effective half-life, the entire dose is accumulated in the first year.

(k) Average value for male and female gonadal doses from Reference 19.

(l) Use Ga-72 values from Reference 22 divided by 3 to account for lower energies.

(m) Values for Nb-95 are used due to the similarity of radiation (β energy is about the same and Nb γ's somewhat higher). Chemical difference is acknowledged.

(n) Values for Xe-133 are used. Factors are divided by 3.6 to allow for different photon energies.

(o) Assuming an effective half-life of 1137 days ($\approx$ 3 years), 10% of the ulimate dose accumulates in 1 year.

(p) Assuming an effective half-life of 800 days ($\approx$ 2 years), 25% of the ultimate dose accumulates in 1 year.

(q) See Safeguards (Chapter VI) for isotopic mixture details.

(r) Values for mixtures calculated are discussed in the text.

(s) Waste is modeled as Cs-137 as suggested in Reference 1.

(t) Mixed corrosion and fission products are modeled as Co-60 as suggested in Reference 1.

9.2 Additional Dosimetric Parameters

Several additional dosimetric parameters are required to perform the calculations. These include total photon energy per disintegration, average photon energy, airborne fraction, particle size, resuspension dose factor, lung mortality type, bone cancer type, thyroid cancer type, and cloudshine dose factor. These parameters are discussed in the following subsection and the results are summarized in Table 59.

9.2.1 Total Photon Energy per Disintegration

The values for total photon energy per disintegration were computed using energy level diagrams in Reference 26. Each decay scheme was examined and each fractional occurrence and its associated photon energy were multiplied and summed. The effects of daughter products were included where appropriate. An average value for spent fuel was computed using the previously-discussed isotopic mixtures and energy level diagrams in Reference 26.

9.2.2 Average Energy of Emitted Photons

The average energy of a photon emitted by a particular radionuclide was calculated using decay schemes in Reference 26. The photon energies were weighted by their respective fractional occurrences.

9.2.3 Airborne Fraction[1]

The fraction of material released in an accident which becomes airborne depends upon the accident environment. A container may be crushed beneath a truck, in which case very little material becomes airborne, or it may bounce into the air following the impact and disperse its entire contents. For most small packages, the fraction

TABLE 59

Additional Dosimetric Parameters

Isotope	Average Photon Energy (meV)	Average Total Photon Energy/dis (meV)	Aerosolized Fraction	Particle Size (μm)	Resuspension Dose Factor(a)	Lung Early Mort. Type	Bone Type	Thyroid Type	Cloudshine Dose Factor(c) (mrem/yr/μci/ml)
H-3	0	0	1.0	1.0	1.0*	1	2	1	0
C-14	0	0	1.0	1.0	1.6	2	2	1	0
Na-22	0.78	1.27	1.0	1.0	1.59	2	2	1	1.88E10
Na-24	2.0	4.12	1.0	1.0	1.0	1	2	1	3.14E11
Mg-28	1.1	3.15	1.0	1.0	1.09	1	2	1	1.1E10
P-32	0	0	1.0	1.0	1.09	1	2	2	0
P-33	0	0	1.0	1.0	1.1	1	2	1	0
S-35	0	0	1.0	1.0	1.4	2	2	2	0
K-43	0.49	.99	1.0	1.0	1.0	1	2	1	8.72E9
Ca-45	0.0	2.5E-7	1.0	1.0	1.47	2	2	1	0
Cr-51	0.3	0.029	1.0	1.0	1.1	1	2	1	1.52E8
Fe-55	0.0	0	1.0	1.0	1.59	2	2	2	1.16E5
Co-57	0.12	.137	1.0	1.0	1.52	2	2	1	1.65E9
Fe-59	1.18	1.18	1.0	1.0	1.31	1	2	1	9.47E9
Co-60	1.25	2.5	1.0	1.0	1.61	2	2	1	1.59E10
Ga-67	0.17	.208	1.0	1.0	1.1	1	2	1	2.02E9
Se-75	0.22	.391	1.0	1.0	1.44	2	2	1	5.7E9
Kr-85	0.5	.002	1.0	1.0	1.0	1	2	1	1.53E3

TABLE 59 - continued

Isotope	Average Photon Energy (meV)	Average Total Photon Energy/ dis (meV)	Aerosolized Fraction	Particle Size (μm)	Resuspension Dose Factor(a)	Lung Early Mort. Type	Bone Type	Thyroid Type	Cloudshine Dose Factor (c) (mrem/yr/μci/ml)
Sr-89	0.0	0	1.0	1.0	1.31*	1	2	2	0
Sr-90	0	0	1.0	1.0	1.52*	2	2	2	0
Mo-99	0.5	.279	1.0	1.0	1.1	1	2	1	1.4E9
Tc-99m	0.14	.143	1.0	1.0	1.0	1	2	1	1.71E10
In-111	0.20	.419	1.0	1.0	1.1	1	2	1	6E9*
Sn-113	0.3	.398	1.0	1.0	1.44	2	2	1	9.94E7
In-114m	1.3	.23	1.0	1.0	1.32	1	2	1	7.54E8
I-123	0.16	.168	1.0	1.0	1.0	1	2	2	1.72E9
I-125	0.04	.035	1.0	1.0	1.35	1	2	2	2.61E8
Xe-127	0.15	.284	1.0	1.0	1.0	1	2	1	7.E8*
I-131	0.64	.385	1.0	1.0	1.09*	1	2	2	3.41E9
Xe-133	0.08	.081	1.0	1.0	1.0	1	2	1	5.02E8
Cs-137	0.66	.619	1.0	1.0	1.62*	2	2	1	.499E10
Eu-152	0.68	.903	1.0	1.0	1.62	2	2	1	1.E10*
Ir-192	0.37	.827	1.0	1.0	1.3	1	2	1	1.E10*
Hg-197	0.08	.081	1.0	1.0	1.1	1	2	1	9E8
Au-198	0.4	0.4	1.0	1.0	1.1	1	2	1	3.6E9
Tl-201	0.16	.06	1.0	1.0	1.1	1	2	1	0

TABLE 59 - continued

Isotope	Average Photon Energy (meV)	Average Total Photon Energy/ dis (meV)	Aerosolized Fraction	Particle Size (μm)	Resuspension Dose Factor(a)	Lung Early Mort. Type	Bone Type	Thyroid Type	Cloudshine Dose Factor(c) (mrem/yr/μci/ml)
Hg-203	0.3	.279	1.0	1.0	1.32	1	2	1	2.66E9
Po-210	0.8	0	1.0	1.0	1.62	3	1	2	0
Ra-226	0.2	1.64	1.0	1.0	1.62	4	1	1	7.52E7
U-235	0.126	.126	.05(b)	7.0	1.63*	4	1	1	1.7E9
U-238	0.02		.05(b)	7.0	1.63*	4	1	1	6.6E6
Am-241	0.06	.066	1.0	1.0	1.6*	4	1	1	2.94E8
Cf-252	1.0		1.0	1.0	1.59	3	2	1	4.74E9
Spent Fuel	.655	.325	1.0	1.0	1.6	2	1	1	5.E9*
Waste	.66	.619	.05	1.0	1.62	2	2	1	.499E10
MF + MC	1.25	2.5	1.0	1.0	1.61	2	2	1	1.59E10

(a) Asterisked values are taken from Reference 27, all others are taken from Figure six by half-life.

(b) Normally shipped as large shipments of LSA material.

(c) Asterisked values are estimated.

which becomes airborne is assumed to be 1.0. However, certain shipments, notably fuel cycle and waste material, may involve large quantities of material (10^5 to 10^6 grams per package). An assumption of unity airborne fraction for such shipments would be excessively conservative, since it would be difficult, if not impossible, to make such large amounts of material airborne.

The methods by which material becomes airborne can be divided into 4 principal categories: (1) wind resuspension of spilled contents, (2) impact or fire-driven pressure rupture, (3) fire entrainment of spilled contents, and (4) explosion. By examination of potential accident environments, it was determined that the pressure-rupture accident is the only mechanism which occurs in a significant proportion of accidents and with a significant potential release. Even when it does occur, not all of the material ejected from the container would become airborne. The situation is analogous to throwing a handful of sand into the air: most of it falls back down, with only a small portion of it becoming airborne for any length of time. It was estimated that on the average, no more than 5% of the released material from a large shipment becomes airborne.

9.2.4 Particle Size

As discussed in Appendix H, the respirability of a material is a function of the aerodynamic diameter of the particle (see Appendix H, Figure 4). However, information on actual particle sizes of material is difficult to obtain. Some information on U_3O_8 and plutonium is available[1] and this information was used for shipments of those materials. In the absence of data for other materials, an aerodynamic diameter of one micrometer was assumed.

9.2.5 Resuspension Dose Factor (RDF)

In order to make a full analysis of actual inhalation hazard, the phenomena of deposition and resuspension must be considered. As the cloud of aerosolized material is transported by the wind, material is removed from the cloud by dry deposition processes and deposited on the ground. (Wet deposition, i.e., deposition caused by scavenging due to rain or snow, is not considered in the model. This neglect of wet deposition will mean that the inhalation dose calculation overestimates the population dose in areas where precipitation can interact with the aerosol cloud.) Dry deposition continually removes material from the cloud and reduces the downwind concentration. Its effect is estimated by depleting the total quantity of material which would contribute to inhalation dose by the amount of material deposited between the source release point and a point of interest. The amount of material deposited at any point is calculated using a deposition velocity, v_d (m/s), which, when multiplied by the time integrated concentration (ci-sec/m^3), yields the amount deposited D (ci/m^2). A value of 0.01 m/sec is used for v_d based on a previous analysis[18] and for consistency with the resuspension model used in this document.[27]

Resuspension occurs when particulate material deposited on a surface is made airborne as a result of mechanical forces (walking, vehicular traffic, plowing, etc.), and/or surface wind stress (as in sandstorms or blowing snow). The resuspended material becomes available for inhalation by people in the contaminated area and can cause an additional component of radiation dose which accumulates with time. Methods used to calculate resuspension effects involve an empirical "resuspension factor," K (m^{-1}), which is the ratio of the air concentration at a point to the surface concentration just below that point in the contaminated area. An initial value of 10^{-5} m^{-1} decreasing exponentially with a 50-day half-life to a constant value of 10^{-9} m^{-1} is used in this model to evaluate the dose contributed by resuspension.[18,27] Because of radioactive decay, materials whose radioactive half-lives are short provide little resuspension dose, whereas nuclides whose radioactive half-lives are long may increase the initial dose by as much as a factor of 1.6 over the dose received during actual cloud passage.

Since Reference 27 does not include all the isotopes of interest in this report, a plot of radioactive half-life vs. resuspension dose factor (RDF) (Figure 5) was compiled from data in Reference 27 and this curve was used to determine RDF for untabulated isotopes.

Although one might expect that the deposition and resuspension phenomena might be somewhat different inside buildings, the experimental evidence summarized in Reference 18 (Table VI-E-3) indicates that this is probably not true. Values for interior resuspension factors are essentially the same (within the large range of experimental uncertainty) as exterior factors. Hence the same value for RDF is used in both cases in the model.

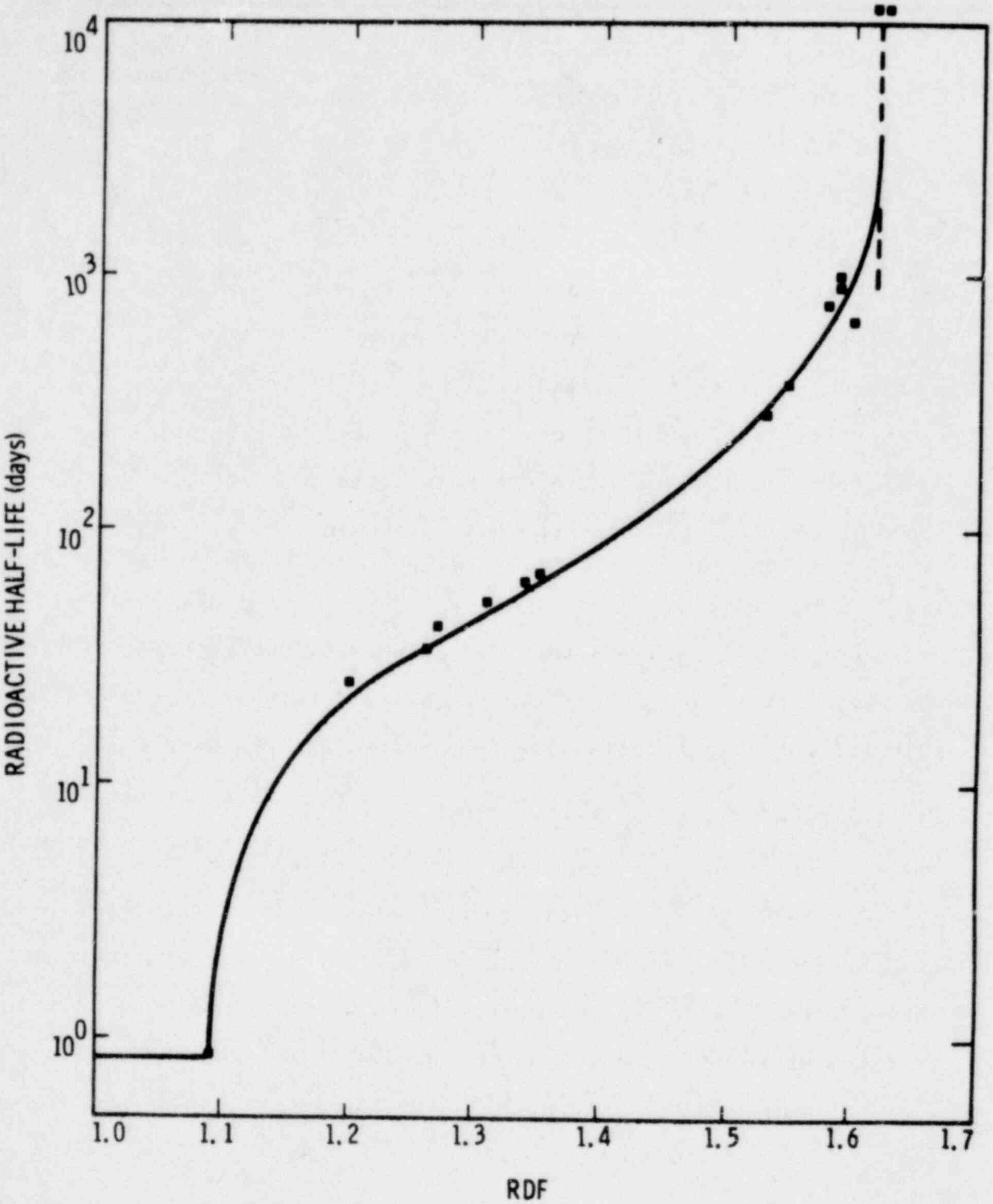


Figure 5. Plot of Radioactive Half-Life vs. Resuspension Dose Factor

9.2.6 Bone Cancer Type, Thyroid Cancer Type

As discussed in Appendix H, the LET of a radiation can greatly affect its potential as a carcinogen. High LET materials (referred to as bone Type 1) are more effective at inducing bone cancer than low LET materials (referred to as bone Type 2). Similarly, thyroid cancer is much more effectively induced by irradiation of the tissue surrounding the thyroid gland than by direct thyroid irradiation by short-range particulate emitters such as I-123, I-125 and I-131. The external irradiators are referred to as thyroid Type 1 and the internal emitters are referred to as thyroid Type 2.

9.2.7 Lung Fatality Type

Appendix H discusses the four various dose-effect relationships for early fatalities from acute pulmonary dysfunction. Values are selected for each material based on half-life and LET.

9.2.8 Cloudshine Dose Factors (CDF)

Cloudshine dose factors representing values for dose received due to immersion for one year in a cloud of a fixed concentration were extracted from Reference 20. The units are mrem/year/μci/ml. The effects of daughter products are, in general, not included. In cases where the isotope did not appear in Reference 20, values were estimated using isotopes with similar photon energy per disintegration and radioactive half-life.

10. Meteorological Data

The initial meteorological data were obtained from an Urban Air Pollution study conducted by New York University to develop an air pollution model for the distribution of SO_2 in New York City.[28] This study attempted to express the information in a manner useful to those studying the dynamics of the urban boundary layer as well as the distribution of pollutants within the atmosphere over New York City. The original data were collected during twelve test periods of from three to five days duration during the period September 1965 to December 1966. In addition, preliminary data were collected during the period July 1964 to April 1965 and other data were collected at intermediate times. Of the twelve test periods, one was cancelled before data collection began and in the succeeding years data have been lost from several of the other sets. Reference 28 selected three sets of complete tests for documentation because of the interesting meteorological conditions, observed SO_2 patterns, overall data quality and previous analysis using a Gaussian puff model.[29] Descriptions of the conditions for the eleven days for which detailed information has been supplied are listed below.

10.1 Test 6

10.1.1 March 8, 1966: A long wave trough was over the northeast with jets through the Ohio Valley and off of the coast at Martha's Vineyard. At the surface, a dynamic high dominated the east.

10.1.2 March 9, 1966: The long wave trough weakened and the jet moved northward into New York State (NYS). The highest speeds moved into Maine and a short wave ridge moved into the southwestern part of the Ohio Valley. The surface high moved northeast across the Ohio Valley into NYS. By 1200Z*, it began to move south.

10.1.3 March 10, 1966: The long wave ridge aloft was building over the western Ohio Valley. The jet maximum was accompanying a short wave ridge and was losing strength. The surface high became stationary over Norfolk, Virginia, and began changing its thermal structure. By 2100Z a cold front had just passed Watertown, New York (moving south) and the high was breaking down.

10.1.4 March 11, 1966: A second jet maximum was over Quebec in association with a well-developed short wave trough and a closed low at 500 mb** over Montreal. The front moved through New York City at 1200Z. Following the front, there was ridging from a dynamic high over Quebec. The ridge was bridging the front in the New York City area during the afternoon.

10.1.5 March 12, 1966: The upper level system moved eastward across the maritime provinces and a weak short wave ridge developed in association with the convergence zone of the jet maximum. The long wave pattern remained unchanged. By 0300Z the surface front moved southward to Washington, DC, and the high moved south-southeast with its center remaining in Quebec.

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*The symbol Z refers to time zone including Greenwich, England. This serves as a universal time base.

**"mb" stands for millibars.

10.2 Test 10

10.2.1 Nov. 15, 1966: At 0000Z, the jet was through the Ohio Valley and off of the coast at Cape Hatteras. The axis of the long wave trough was through an area northeast and east of NYC. By 1200Z, the jet moved to a position north of the city, and there was a jet maximum over northwest Ontario. At the surface at 0600Z, a dynamic high was centered in northwest Ontario, with ridging into the Ohio Valley.

10.2.2 Nov. 16, 1966: The flow was becoming more zonal, with the jet split into two cores. The primary core was over southern Quebec, while the secondary core was over the southern Ohio Valley. At 0000Z, the surface ridge was in NYS, while six hours later the high was centered over Alabama. By 1800Z, the flow at NYC was southwest, with a warm front near Buffalo.

10.2.3 Nov. 17, 1966: The two jet cores merged and came off of the east coast at Washington, DC. A strong maximum was developed over Wisconsin. At 0000Z, the surface front extended from Watertown, NYS to Providence, RI. It then moved northward and became quasi-stationary in northern New England, with southwesterly flow remaining over NYC.

10.3 Test 12

10.3.1 Dec. 6, 1966: At 0000Z, a dynamic high at 850 mb over Charlestown, SC, dominated the entire east coast. It was beginning to change its structure to a warm core high. The surface pattern was generally the same as that at 850 mb.

10.3.2 Dec. 7, 1966: The high at 850 mb was a stationary warm core high centered at 30N and 75W. The surface pattern was generally the same as that at 850 mb.

10.3.3 Dec. 8, 1966: By 0000Z a front at 850 mb was pushing into the Ohio Valley, increasing the wind speed over NYC up to 30 kts. (from the west). By 0600Z, the surface high was off of the coast, and there was strong southwesterly flow through the entire east coast.

Wind data from the various stations*, located in a large rectangle centered on the west side of midtown Manhattan, were measured from half-hour to half-hour and data so collected were averaged and assigned to the center hour, except for airport, military and Coast Guard stations where standard hourly synoptic observations were taken. Hourly-average wind speed and direction data were plotted on maps by Bornstein, et al, for each hour during the three "primary" test periods.[28] Desiring continuity, Bornstein reanalyzed the original New York University maps for even numbered hours for the days in the selected test periods, taking into account the problems with individual data collection sites and missing data.

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*1) 14 airport stations,
2) 4 military bases,
3) 10 Coast Guard bases,
4) 15 utility companies,
5) 14 industrial sites,
6) 29 public agencies and institutions,
7) 11 sites set up by New York University.

Having obtained the hourly maps for each of the eleven days, maps for this New York City study area were constructed by scaling the information from Bornstein.

Data obtained from Reference 28 were analyzed to obtain approximations for wind direction and magnitude for each hour of each day, yielding eleven values for wind direction and speed for each hour of the day as shown in Table 60. From these values, a single map was prepared using typical values for each hour of the day. A map of the NYC study area was then prepared for each hour of the day with wind direction and speed values for each unit cell listed. These data serve as the input for the meteorological model.

TABLE 60

EXAMPLE OF WIND DIRECTION AND SPEED FOR ELEVEN STUDY DAYS[30]

0100 hrs	Date	Approximate Wind Direction	Speed
1	3/8/66	SE	10-20
2	3/9/66	SW	5-10
3	3/10/66	NE & E	15
4	3/11/66	NE	8-10
5	3/12/66	W	5-7
6	11/15/66	SE	10-15
7	11/16/66	S	5-10
8	11/17/66	N	4-6
9	12/6/66	NE	5-8
10	12/7/66	W	4-6
11	12/8/66	N	3-6

References

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APPENDIX B

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APPENDIX C

Operating Procedures for the Task Group

A task group is being formed by Sandia Laboratories to facilitate its environmental impact assessment on the transportation of radioactive materials near and through high density population areas--a study currently being performed under contract to the Nuclear Regulatory Commission. This task group will assist Sandia in the development of an environmental assessment model. The purpose of the task group is to provide a forum for the interchange of ideas and information rather than to arrive at a consensus. In the interest of meeting schedules for the completion of the work, Sandia may exercise discretion in the use of any proposed ideas and information. Sandia will assume full responsibility for the contents of any reports issued as a result of this work.

Sandia will arrange and conduct meetings of the task group as required. A Sandia employee will act as moderator at the sessions. Four or five meetings may be required to meet the present objectives of the program. Approximately twenty members have been selected to participate in the initial meeting scheduled for September 20, 1976, in New York City.

Sandia is requesting persons to participate in the task group on the basis of their reputations in the areas of interest and to obtain a balanced, broad viewpoint. The anticipated membership is comprised of interested individuals from federal, state, and local agencies as well as people involved in related industrial, academic, and environmental public interest areas. Compensation, when required for travel expenses, will be in accordance with the practices followed by the Federal government; if compensation for time spent away from regular employment is required, the payment will not exceed the GS-18 scale of $145/day.

The first meeting is scheduled to last one day. Public notice will be made of the meeting and provision will be made for up to twenty-five observers. A luncheon will be provided for the invited participants with coffee and donuts available for all attendees.

Minutes will be taken at the meetings. A copy of these minutes will be mailed to the participants for editing no later than one week after the meeting. After allowing two weeks for incorporating changes made by the participants, the completed minutes will be transmitted to NRC for placement in the Public Document Room (1717 H Street, N.W., Washington, D.C.) where they will be available for public inspection. The proceedings and operation of the task group are open to the public; the membership and operation of the group may be noted in Sandia and NRC publications. Invited participants may bring observers or advisory staff to meetings as they deem appropriate; but to avoid logistical difficulties, active participation in the group discussions and payment of expenses will be limited to the invited participants only. Because of their special knowledge of and relation to this study, various staff members of Sandia Laboratories and NRC will be involved in the discussions as appropriate.

APPENDIX D

Dose Model for Accident-Free Transport of Radioactive Materials

1. Introduction

Since virtually all packages of radioactive material emit some external penetrating radiation, persons located adjacent to radioactive material shipping routes receive small doses of radiation as an inevitable consequence of the shipment of these materials. This dose, referred to as dose due to accident-free transport, is defined as that dose which is received from transport involving no vehicular accident of packaging or handling abnormalities (i.e., improper labeling, crushing by fork lifts, omission of O-rings, etc.) which might cause increased exposure. Evaluation of doses resulting from vehicular accidents is considered in Appendix E, and doses resulting from packaging or handling abnormalities are discussed in Chapter V.

The model for evaluation of dose due to accident-free transport is based on a parameter called Transport Index (TI), defined in the Code of Federal Regulations as the dose rate at a distance of 3 feet from a package measured in mrem/hr.[1] Since the measured value for this parameter is noted on each package, it provides a convenient benchmark for computing the dose from accident-free transport.

The entire development of the dose computation is based on the following formula for dose rate from a point source of ionizing radiation:

$$DR = \frac{Ke^{-\mu r} B(r)}{r^2}, \qquad (1)$$

Where DR = dose rate (mrem/hr)*

K = dose rate factor (mrem-m^2/hr)

μ = attenuation coefficient (m^{-1})

r = distance from source (m)

$B(r)$ = dose buildup factor (dimensionless).

In this case, $e^{-\mu r}$ accounts for the attenuation of dose rate as the photons penetrate the absorbing medium; $1/r^2$ accounts for the 4π geometric dose rate reduction; and $B(r)$ accounts for the dose buildup caused by inelastic photon scattering in the attenuating medium.

If a package shape factor, K_o is defined to account for the actual package dimensions, and if TI is taken to be the dose rate in mrem/hr at a distance of 1 meter from the surface of the package, the dose rate at some distance from a shipment of radioactive materials containing a certain number of packages (PPS) can be expressed as:

$$DR = \frac{K_o * TI * PPS * e^{-\mu r} * B(r)}{r^2} \quad . \qquad (2)$$

The dose expressions for radiological effects in accident-free transportation are obtained by manipulating this expression.

The Code of Federal Regulations addresses two types of TI. Radiation TI is equal to the dose rate measured 3 feet from the package, and fissile TI is computed based on criticality considerations. Since the TI rating of a package is defined as the larger

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*A complete list of variables, constants, functions, etc. used in the equations in this appendix is found in Addendum 1.

of the two, this assessment assumes that the TI quoted is radiation TI. This may overestimate dose effects for some fissile packages.

Figure 1 diagrams the manipulation which is of prime interest in determining integrated population exposures. The question to be answered is "what integrated dose will be received by an individual at a specified perpendicular distance, d, from the path of a vehicle carrying radioactive material as that vehicle passes?"

Initially one notes that

$$DR = \frac{dD}{dt}, \tag{3}$$

where D = total dose.

By definition,

$$dt = \frac{dx}{v}, \tag{4}$$

where v = velocity (assumed to be constant). By combining Equations 1, 3, and 4, and integrating an expression for total dose from a shipment traveling from $-\infty$ to $+\infty$ past the individual, the following expression is obtained:

$$D = \frac{K}{V}\int_{-\infty}^{\infty} \frac{e^{-\mu r} B(r) dx}{r^2} \tag{5}$$

By noting that the dose rate function is symmetric about the origin, and by changing the differential to be in terms of r instead of x, the expression for integrated dose becomes

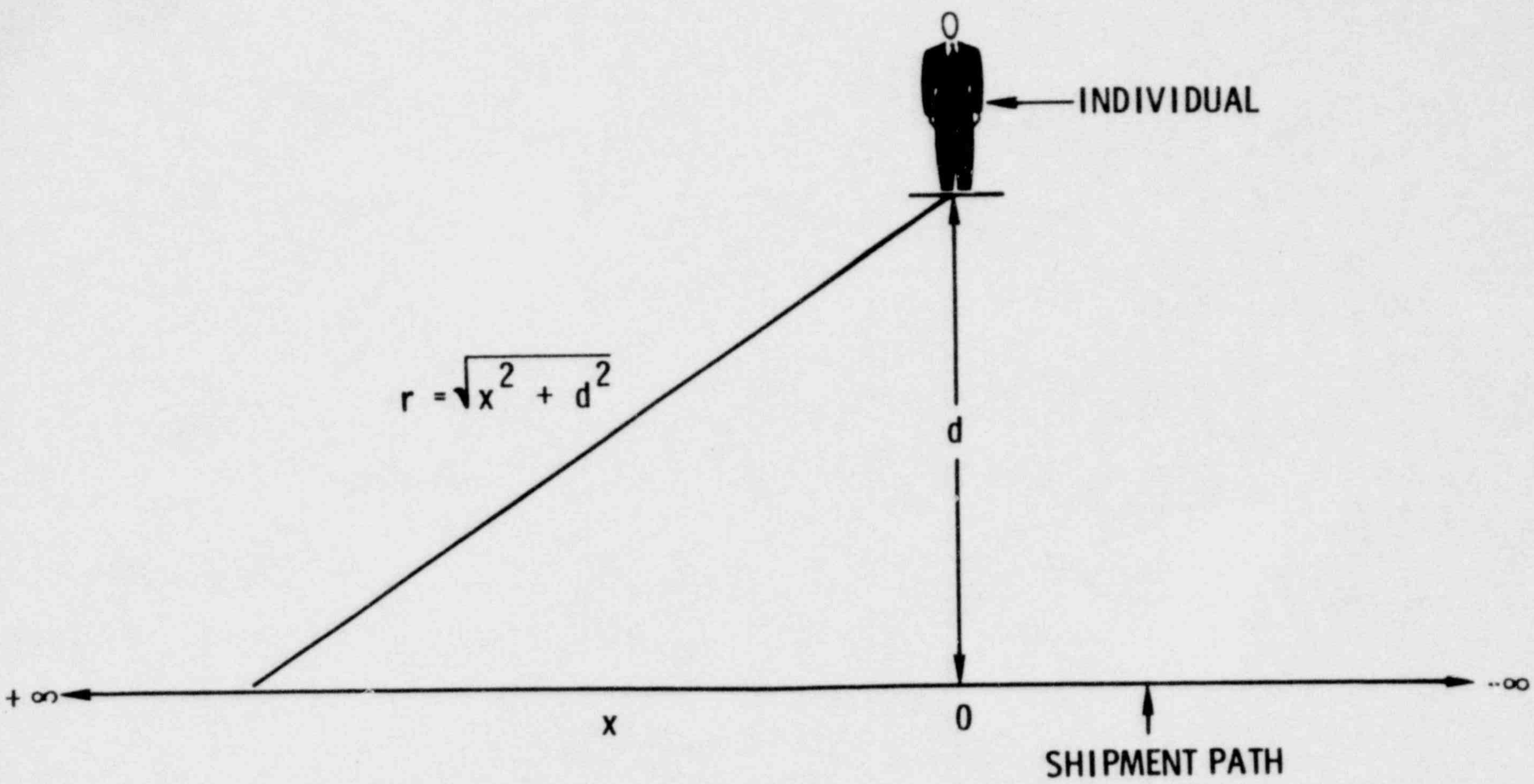


Figure 1. Geometry for Integrated Dose Calculations

$$D = \frac{2K}{V}\int_{d}^{\infty} \frac{e^{-\mu r}B(r)dr}{r(r^2-d^2)^{1/2}} \quad . \tag{6}$$

This expression (which is derived in more detail in Reference 2) forms the basis for most of the integrated dose expressions in the accident-free dose analysis.

Each of the various transport modes (truck, rail, air, and water) has unique characteristics as regards accident-free transport. These will be dealt with individually in the following sections.

2. Dose Due to Accident-Free Truck Transport

2.1 Dose due to accident-free truck transport of radioactive material can accrue to pedestrians, people in vehicles, people in buildings, and crewmen.

The population which is exposed as a result of shipment by truck is divided into six groups: pedestrians, people in buildings, people in vehicles, handlers, crewmen, and warehousemen. Each of these groups will be analyzed in detail in the following subsections.

2.2 Pedestrians

Assume a shipment is moving on a street of width w_{st} at a speed V_s as shown in Figure 2. On each side of that street are sidewalks of width w_s. Assume that equal numbers of pedestrians are moving in each direction at speed v_p at a density given by PedD (persons/km^2). Using these assumptions, the dose received by pedestrians is composed of four doses:

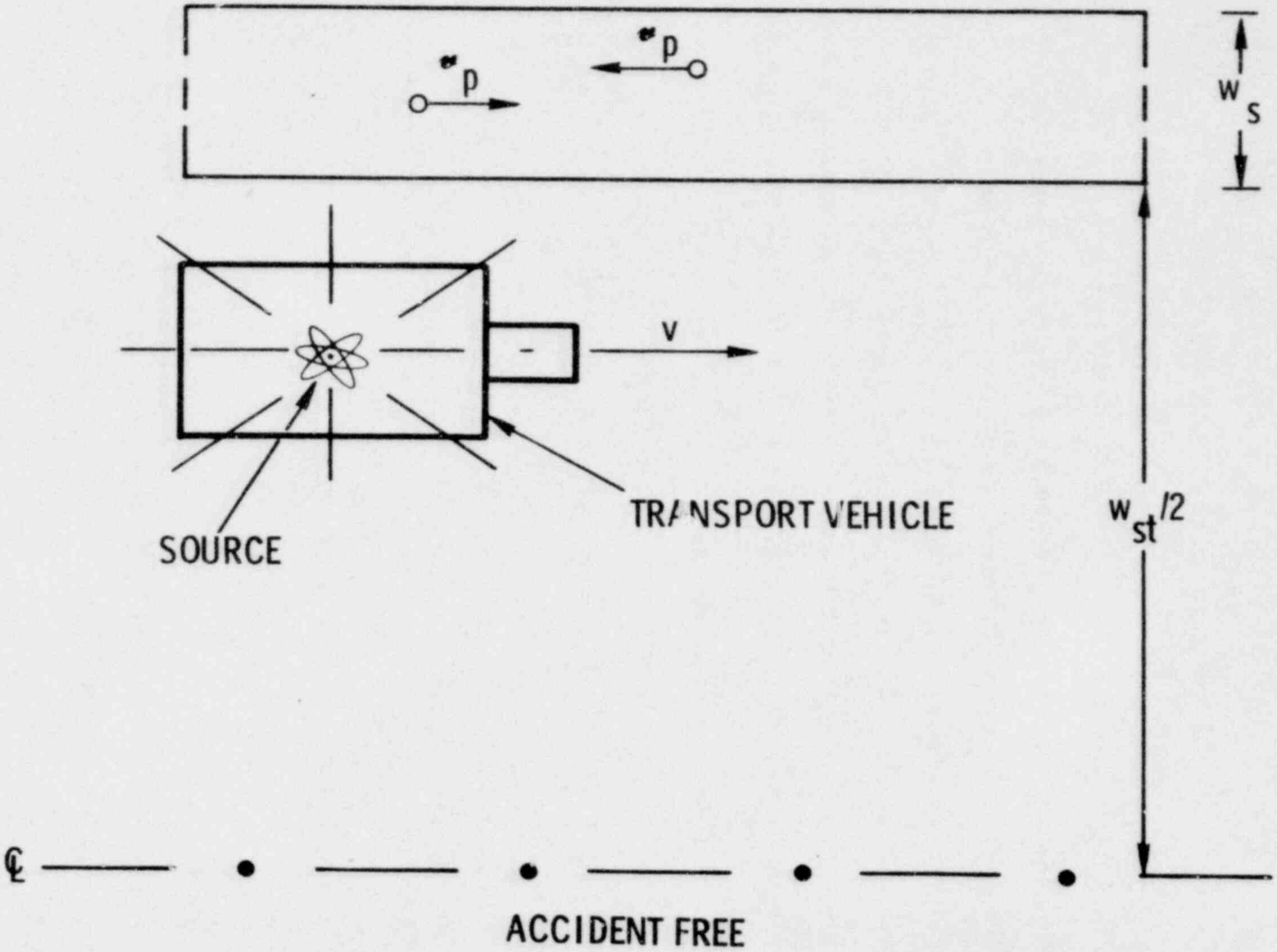


Figure 2. Geometry for Accident-free Dose to Pedestrians

1) Dose to pedestrians moving in the same direction as the shipment on the same side of the street;

2) Dose to pedestrians moving in a direction opposite to the shipment on the same side of the street;

3) Dose to pedestrians moving in the same direction as the shipment on the far side of the street;

4) Dose to pedestrians moving in a direction opposite to the shipment on the far side of the street.

Relative motion between the shipment and the pedestrians is accounted for by considering that the pedestrians are stationary and the shipment is moving past them at a speed of $\overline{V} + v_p$ (situations 2 and 4), or $\overline{V} - v_p$ (situations 1 and 3), where $\overline{V}$ is the average velocity of the vehicle, including both cruising periods and stops at intersections. In general, shipment velocity is much greater than pedestrian velocity. However, under certain extremely congested traffic conditions v_p may be significant with respect to $\overline{V}$.

If it is assumed that the truck travels in the center of either half of the street, the distance to the street edge of the far sidewalk is .75 w_{st} and the distance to the street edge of the near sidewalk is .25 w_{st}. This assumption implies that the width of the vehicle (or package) itself is small when compared with the width of the street. As discussed in Appendix D of Reference 3, the dose received by an individual as the shipment pass can be given by:

$$D(x) = \frac{2K}{V} I(x) \tag{7}$$

where D (x) = Total integrated dose absorbed by an individual at a distance x from the path of a radioactive shipment

K = Dose rate factor for the shipment

v = Shipment speed

x = Perpendicular distance from individual to shipment

$$I(x) = \int_{x}^{\infty} \frac{e^{-\mu r} B(r) dr}{r(r^2 - d^2)^{1/2}} \quad , \tag{7a}$$

where = Attenuation coefficient (for air)

B(r) = Dose buildup function (for air)

D(x) can be integrated to obtain an expression for overall integrated dose on each side of the road:

$$ID = PD * L \int_{d}^{max} D(x)dx, \tag{8}$$

where ID = Total integrated dose

PD = Person density (persons/area)

L = Length of trip (in cell)

d = Perpendicular distance from individual to shipment

max = Maximum distance of interest.

In order to convert the general expression to one applicable to pedestrians, PD becomes PedD; L becomes the length of travel in the cell of interest; d becomes .25 w_{st} or .75 w_{st}; and max becomes (.25 w_{st} + w_s) or (.75 w_{st} + w_s).

The dose received by pedestrians includes a component which results from scattered radiation from the ground surface or from adjacent buildings. This dose, referred to as albedo dose, has three components, as shown on Figure 3. The relative magnitudes of these components are analyzed in Reference 4. All doses are given with reference to the free-air exposure.

Figure 4 shows the experimental relationship between groundscatter albedo and h/d ratio for the given geometry. A typical value of h/d for urban transport vehicles and roadways is .1, so a value of .2 for groundscatter albedo dose is used. There is some variation with energy, but the Ir-192 photon energy is considered typical of transported material. The albedo dose component due to building backscatter is shown as a function of energy in Figure 5. Again, using Ir-192 photon energies as typical, a value of 0.16 for normal backscatter is obtained. The backscatter of groundscattered radiation from buildings is simply the product of .2 and .16 or .032.

When both albedo dose and direct dose are considered, the integrated dose to pedestrians becomes:

$$ID = Q_1 * PedD * L * (2*K_o*TI*PPS) * \frac{L*w_{st}}{A*f_{st}} * ABD *$$

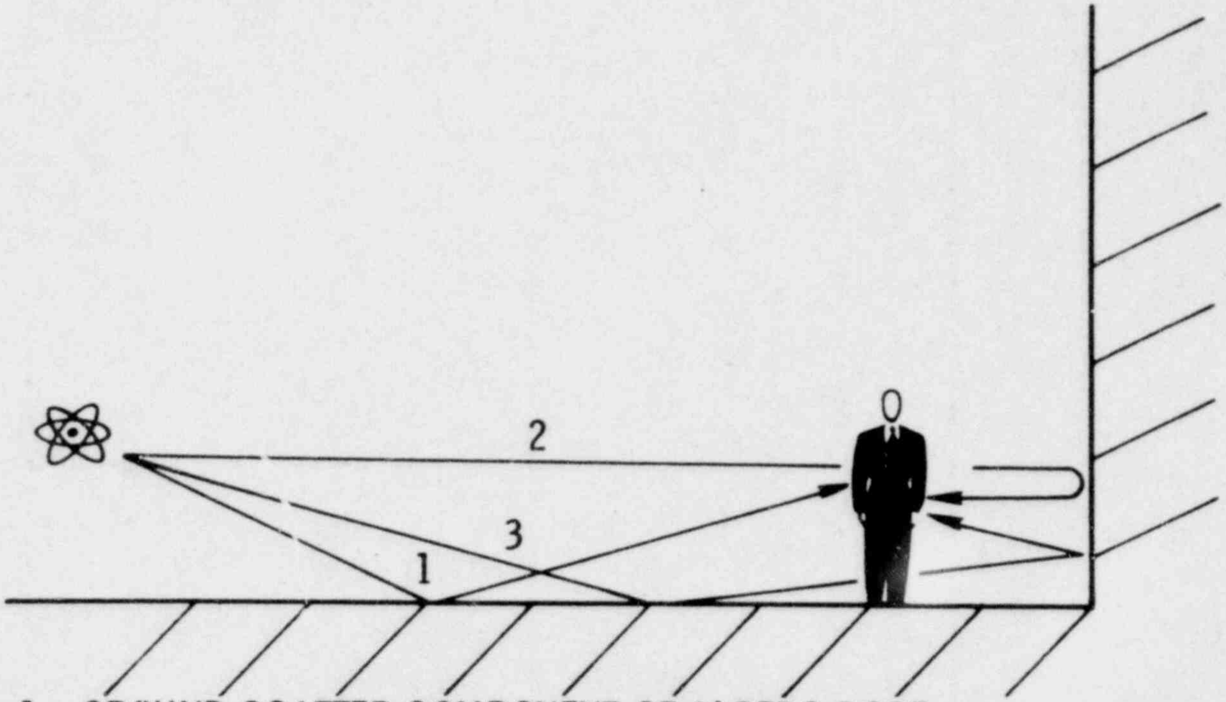
$$\left[\int_{.75w_{st}}^{.75w_{st}+w_s} \frac{I(x)dx}{(\bar{V}-V_p)} + \int_{.75w_{st}}^{.75w_{st}+w_s} \frac{I(x)dx}{(\bar{V}+V_p)} + \int_{.25w_{st}}^{.25w_{st}+w_s} \frac{I(x)dx}{(\bar{V}-V_p)} + \int_{.25w_{st}}^{.25w_{st}+w_s} \frac{I(x)dx}{(\bar{V}+V_p)}\right] , \quad (9)$$

where PedD = Pedestrians per grid square (pedestrians/km^2)

$\frac{L*w_{st}}{A*f_{st}}$ = Fraction of grid square sidewalks adjacent to shipment routes

Q_1 = Units conversion factor

ABD = Albedo dose factor (= 1.39)



1. GROUND SCATTER COMPONENT OF ALBEDO DOSE
2. BUILDING SCATTER COMPONENT OF ALBEDO DOSE
3. BUILDING SCATTER (from ground scatter) COMPONENT OF ALBEDO DOSE

Figure 3. Albedo Dose Contributions

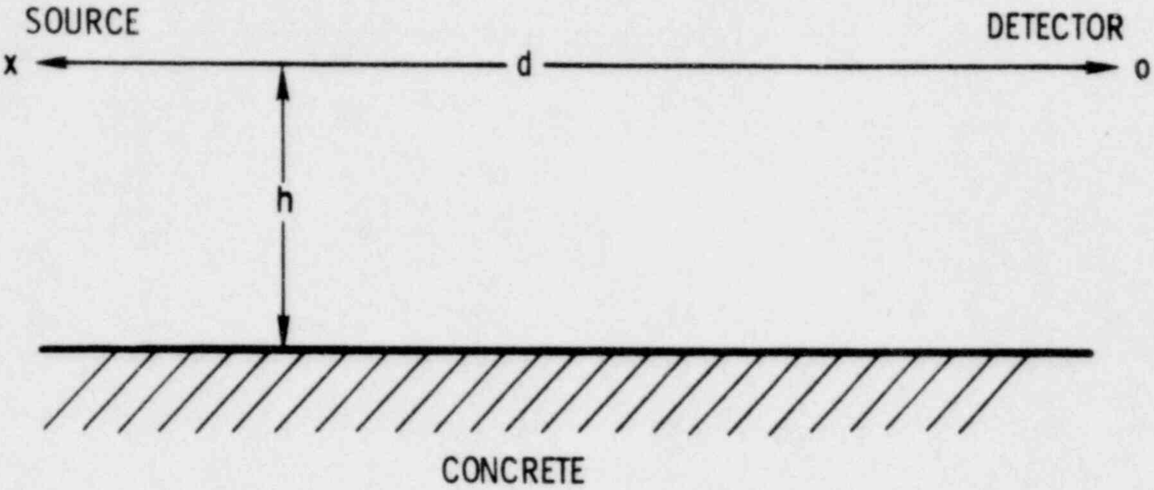


Figure 4a. Geometry for Gamma-Ray Scattering Experiments Performed by Clarke and Batter[4]

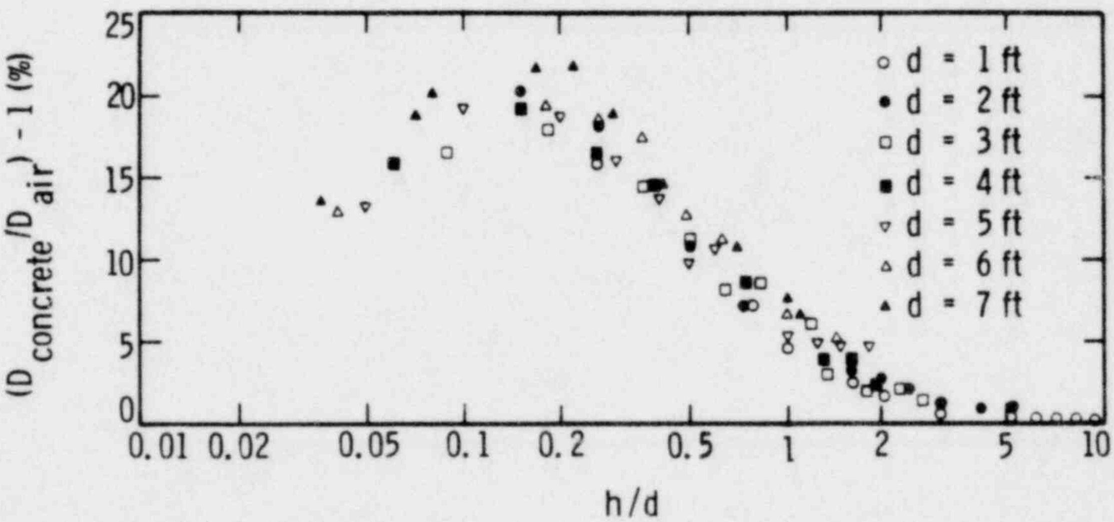


Figure 4b. Increase in Gamma-Ray Dose Rate from a ^{192}Ir Source Due to Scattering from a Concrete Surface[4]

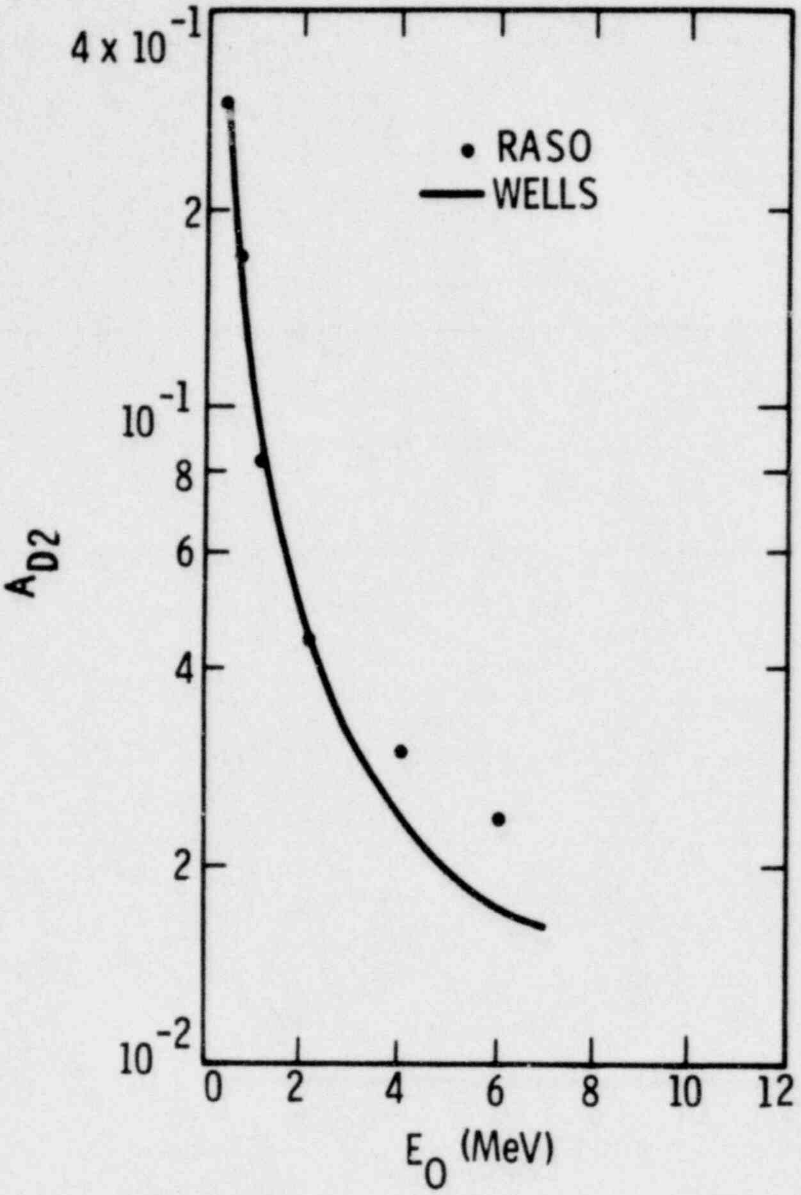


Figure 5. Total Dose Albedos for Gamma Rays Normally Incident on Concrete[4]

$$\bar{V} = \text{Average velocity (m/sec)} = \frac{L}{\frac{L}{V_c} + (\xi * \frac{L}{D'} * \Omega)} = \frac{1}{\frac{1}{V_c} + \frac{Q_2 \xi \Omega}{D'}} \quad (9a)$$

V_c = Cruising velocity (m/sec)

ξ = Fraction of intersections at which the vehicle stops

D' = Average block length (m)

Ω = Delay time at intersections (hr)

Q_2 = Units conversion factor.

The integrals in Equation 9 can be evaluated using zero order Bessel functions*

Two further assumptions which should be noted are:

1. No pedestrian self-shielding is evaluated;
2. No shielding from the transport vehicle, other cargo, or other intervening vehicles is considered.

Two additional factors will now be considered: dose to people moving at right angles to the shipment direction on sidewalks associated with sidestreets, and people moving in front of the shipment while it is stopped at intersections.

The inclusion of pedestrians on sidestreets in the dose calculation can be envisioned as shown in Figure 6. Pedestrians moving parallel to the shipment in the crosswalk area are included in Equation 9. If building shielding is ignored for the moment, the dose received by a person in the cross-hatched area at an arbitrary distance x from the shipment will be given by:

*These Bessel functions and other mathematical forms used to evaluate complex functions are discussed in the addendum to this appendix.

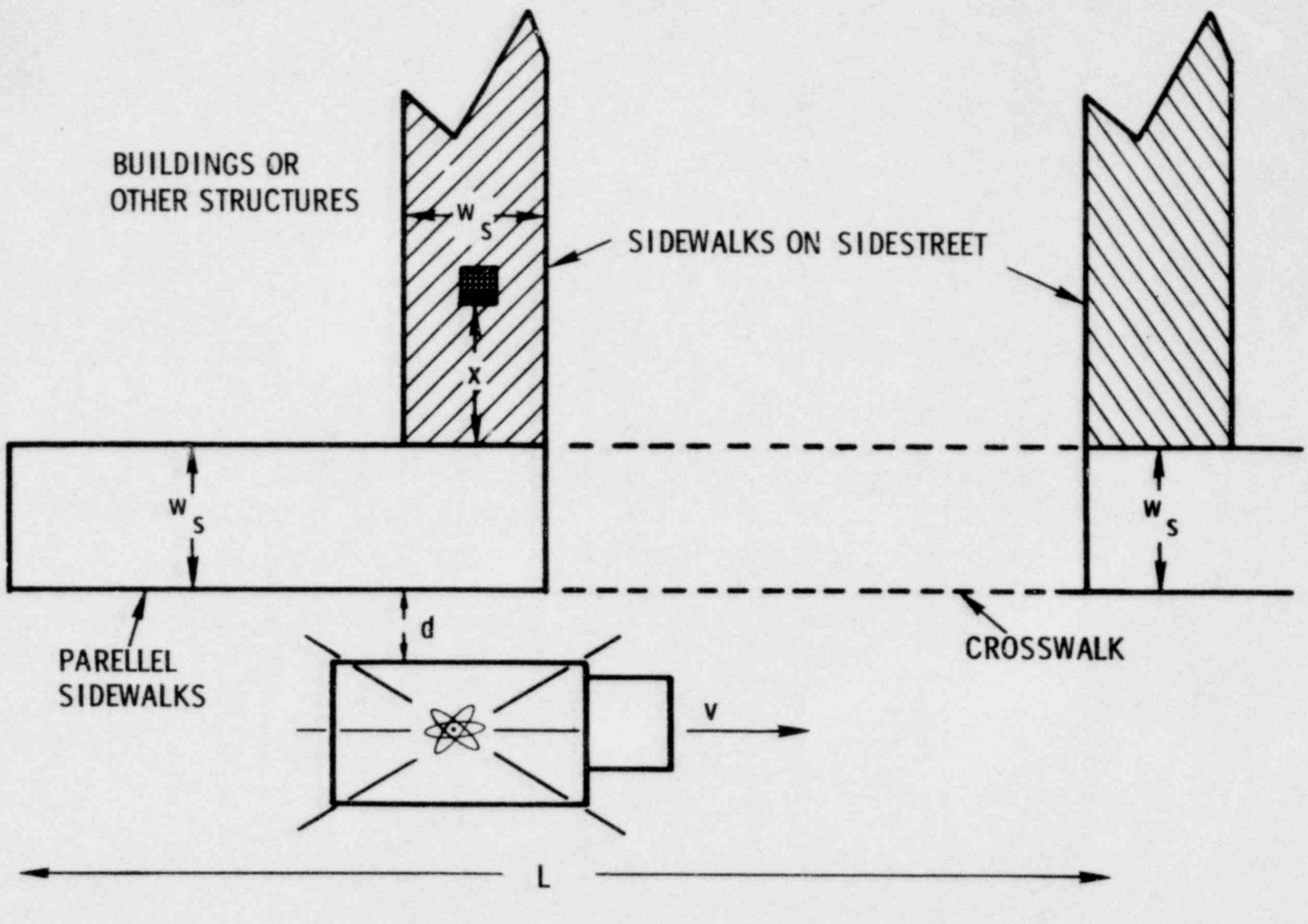


Figure 6. Geometry for Accident-free Dose to Pedestrians on Sidestreets

$$D(x) = \frac{2k}{v} \int_x^{\infty} \frac{e^{-\mu r} B(r)dr}{r(r^2 - x^2)^{1/2}} \ . \tag{10}$$

The integrated dose received by all people on the sidewalk as the shipment passes is, therefore, given by

$$ID_{\perp} = \frac{2k}{v} * PedD* \ w_s * \int_{d+w_s}^{\infty} \left(\int_x^{\infty} \frac{e^{-\mu r} B(r)dr}{r(r^2 - x^2)^{1/2}} \right) dx \ . \tag{11}$$

If it is assumed that people are stationary as the shipment passes, the expression for integrated dose to people moving parallel to the shipment for one block is

$$ID_{\parallel} = \frac{2k}{v} * PedD* \ L * \int_d^{d+w_s} \left(\int_x^{\infty} \frac{e^{-\mu r} B(r)dr}{r(r^2 - x^2)^{1/2}} \right) dx \ . \tag{12}$$

Forming the ratio of the perpendicular and parallel components of pedestrian dose:

$$\frac{ID_{\perp}}{ID_{\parallel}} = \frac{w_s}{L} * \frac{\int_{d+w_s}^{\infty} \left(\int_x^{\infty} \frac{e^{-\mu r} B(r)dr}{r(r^2 - x^2)^{1/2}} \right) dx}{\int_d^{d+w_s} \left(\int_x^{\infty} \frac{e^{-\mu r} B(r)dr}{r(r^2 - x^2)^{1/2}} \right) dx} \ . \tag{13}$$

If it is assumed that an average block is .1 mile long (10 blocks 1 mile), that a sidewalk is 10 feet wide, and that the closest distance of approach of a vehicle to the sidewalk is 10 feet, then the ratio is equal to .07. Since shielding due to intervening structures will further decrease the dose received by pedestrians on sidestreets as the distance from vehicle to the intersection increases, ignoring perpendicular pedestrian flow on sidestreets does not introduce a significant error into the analysis.

The second aspect of the perpendicular pedestrian flow problem is shown in Figure 7. In this case, the source is stationary and the people are moving at a speed v_p across the intersection in front of the stopped vehicle. It can be shown that the dose received by a person walking past the stationary source at a perpendicular distance x at a speed v_p is the same as the dose received at the position of the vehicle if the source were moving by at a perpendicular distance x at a speed v_p. If it is assumed that the vehicle is located at the center of the street, the total dose received by pedestrians who walk across the street in the crosswalk nearest the vehicle can be expressed as

$$ID_{\perp,1} = \frac{2K}{v_p} * w_{st} * PedD * \int_{d}^{d+w_s} \left(\int_{x}^{\alpha_1} \frac{e^{-\mu r} B(r)dr}{r(r^2-x^2)^{1/2}} \right) dx \quad , \qquad (14)$$

where $_1 = (w_{st}/2)^2+x^2 \;^{1/2}$.

Similarly, the dose to people in cross walks on the far side of the street is

$$ID_{\perp,2} = \frac{2K}{v_p} * w_{st} * PedD * \int_{d+w_s+w_{st}}^{d+2w_s+w_{st}} \left(\int^{\alpha_1} \frac{e^{-\mu r} B(r)dr}{r(r^2-x^2)^{1/2}} \right) dx \quad . \qquad (15)$$

A ratio of these values to the dose received during parallel passage can now be formed:

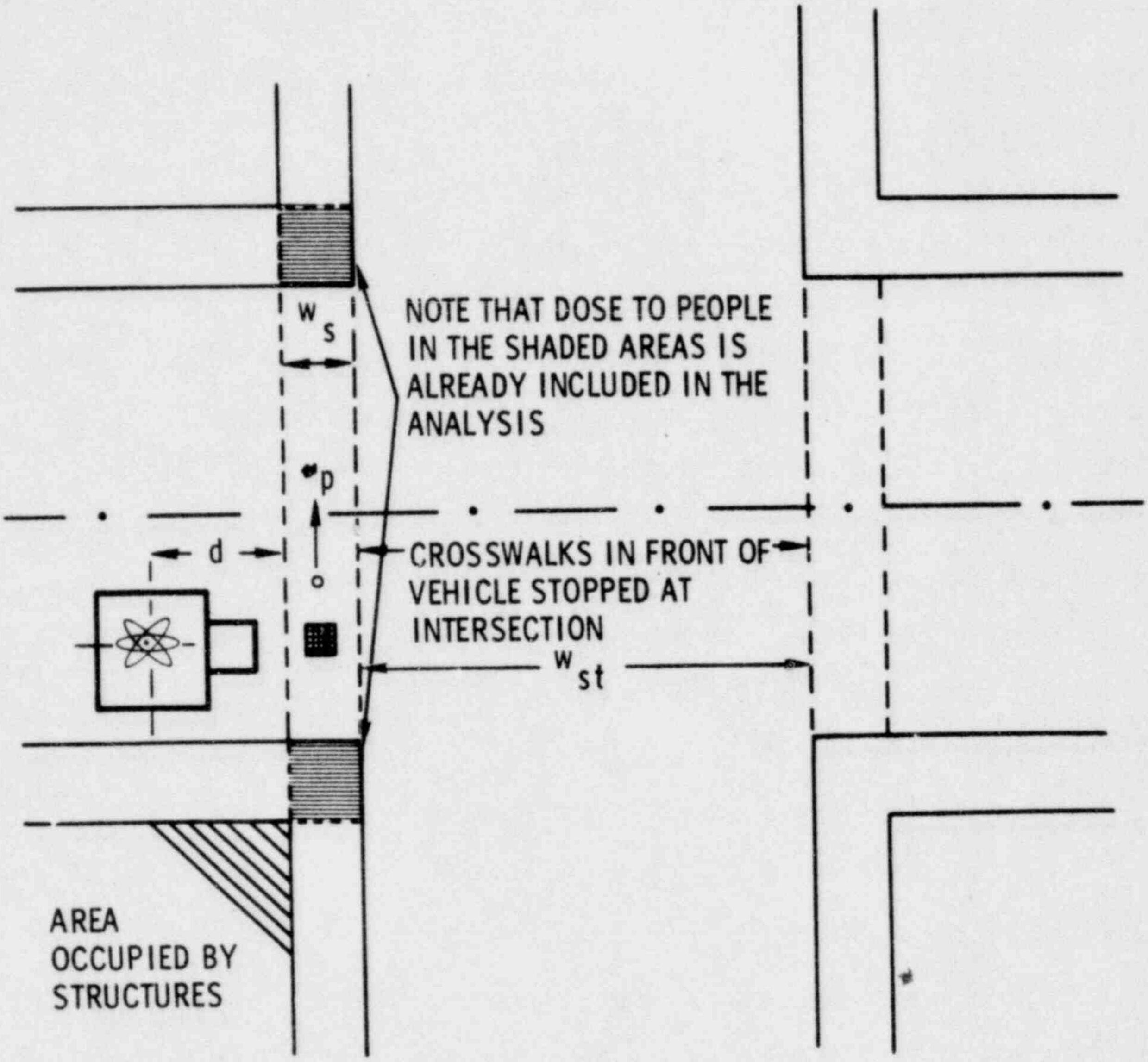


Figure 7. Geometry for Accident-free Dose to Pedestrians in Crosswalks Ahead of Vehicle

$$\frac{ID_{\perp}}{ID_{\parallel}} = \frac{\bar{v}}{v_p} * \frac{L}{w_{st}} * \frac{I_{\perp,1} + I_{\perp,2}}{I_{\parallel}} \quad , \tag{16}$$

where $I_{\perp,1}$ is given by Equation 14, $I_{\perp,2}$ as given by Equation 15 and $I_{\parallel}$ is given by Equation 12.

If the previously mentioned values for L and w_s are used, and if values of 60 feet for w_{st}, 30 feet for d, 2 mph for v_p, and 15 mph for $\bar{V}$ are used, the ratio is .1. In evaluating this, it should be noted that the truck is assumed to stop adjacent to the crosswalk each time it reaches an intersection. This is conservative, since the truck can stop anywhere along the block and probably will not be stopped at each intersection. (The fact that, on the average, a truck will stop at some intersections is considered in the calculation used for $\bar{V}$ in previous equations [see notes on Figure 18].) The ratio drops off rapidly as the distance from the crosswalk increases (R = 0.07 for 40', -.01 for 100'). In consideration of all of these factors, dose received by pedestrians in crosswalks is not included.

2.3 People in Buildings

The formulation used to compute dose to people inside buildings is similar to the formulation used to compute dose to pedestrians. Significant differences are (1) shielding is considered, (2) people are considered stationary inside buildings, and (3) different dose rates occur on different floors in the building. Consider the picture shown in Figures 8 and 9. Radiation which reaches people

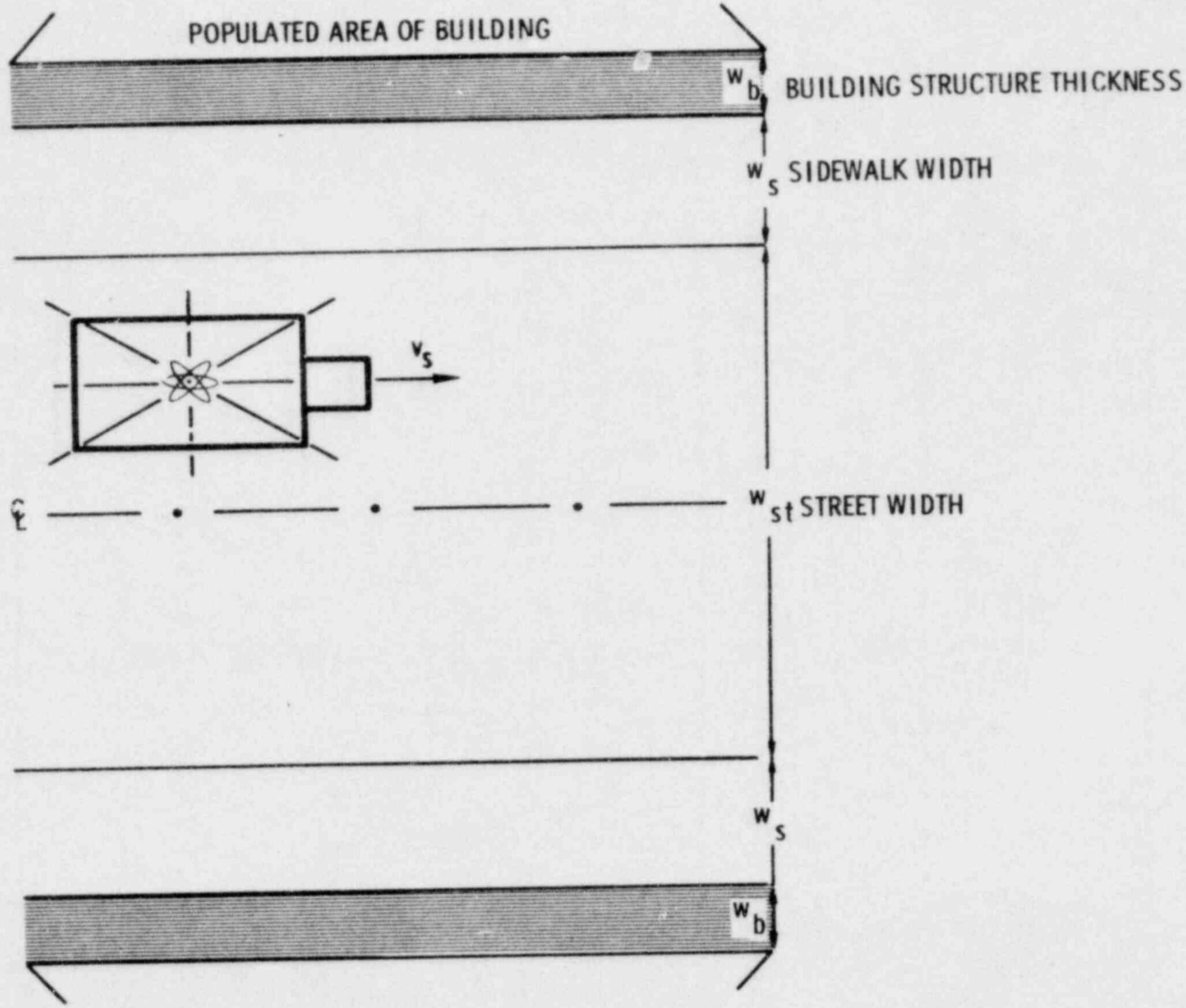


Figure 8. Geometry for Accident-free Dose to People in Buildings

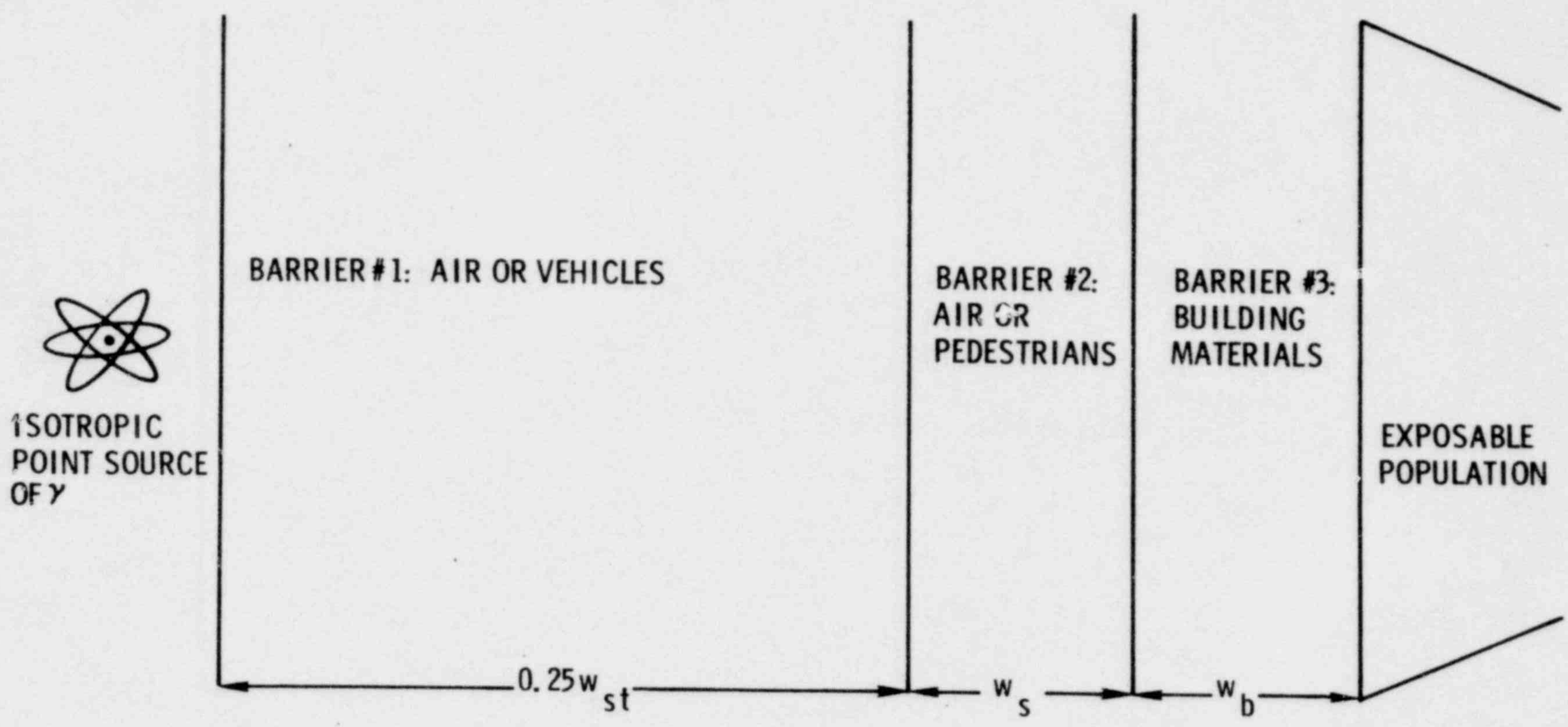


Figure 9. Multiple Slab Geometry

inside the building must penetrate the air (or vehicles) between the source and the sidewalk, the air (or pedestrians) across the sidewalk width, and the building wall.

2.3.1 Building Characterization

In order to discuss the development of this dose mode in much greater detail, building types and building material characterization must be considered. Initially, buildings are characterized by 3 parameters: principal construction material, wall thickness, and building height.

The three shielding properties associated with a wall--thickness, attenuation coefficient, and dose buildup factors will be considered first.

Wall Thickness - In this model, wall thickness is considered a characteristic of various classes of buildings. For example, many single-family residences are either frame construction, using wall board mounted on 2 x 4 studs, or masonry with brick or concrete block with associated cosmetic finishings. Thus, the model allows single-family residences to have either 8 inches of brick/concrete or 4-8" of wood and/or insulating materials as a shield for persons inside. These dimensions are also typical of older, frame-type tenement dwellings or low-rise buildings (e.g., 3-5 floors) where the structural support requirements are minimal. In larger buildings with their increased structural requirements, reinforced concrete is used. Older buildings would probably use reinforced concrete as exterior wall material, whereas new high-rise buildings generally have the supportive area at the center or at corners, and large expanses of plate glass as the fronting material.

To summarize, four examples of possible thickness-material combinations will be considered from a shielding viewpoint:

1) 4"-8" of wood
2) 8"-10" of brick/concrete
3) 24" of concrete
4) .75" of plate glass.[5]

Attenuation Coefficient - The linear-absorption coefficient describes the attenuation of geometric radiation in a given material by photoelectric effect, Compton scattering, and pair production. Values for the coefficient as a function of energy are shown in Table 1 and plotted in Figure 10 for various materials.

Buildup Factor - As gamma radiation passes through an attenuating medium, secondary gamma radiation is produced by Compton scattering. Thus, a dose buildup (caused by the additional dose from secondary radiation) can occur. Reference 6 suggests the following mathematical expression to describe this dose buildup:

$$BF(E,\mu,w_b) = A_1 e^{-\ 1\mu w_b} + A_2 e^{-\ 2\mu w_b} \qquad (17)$$

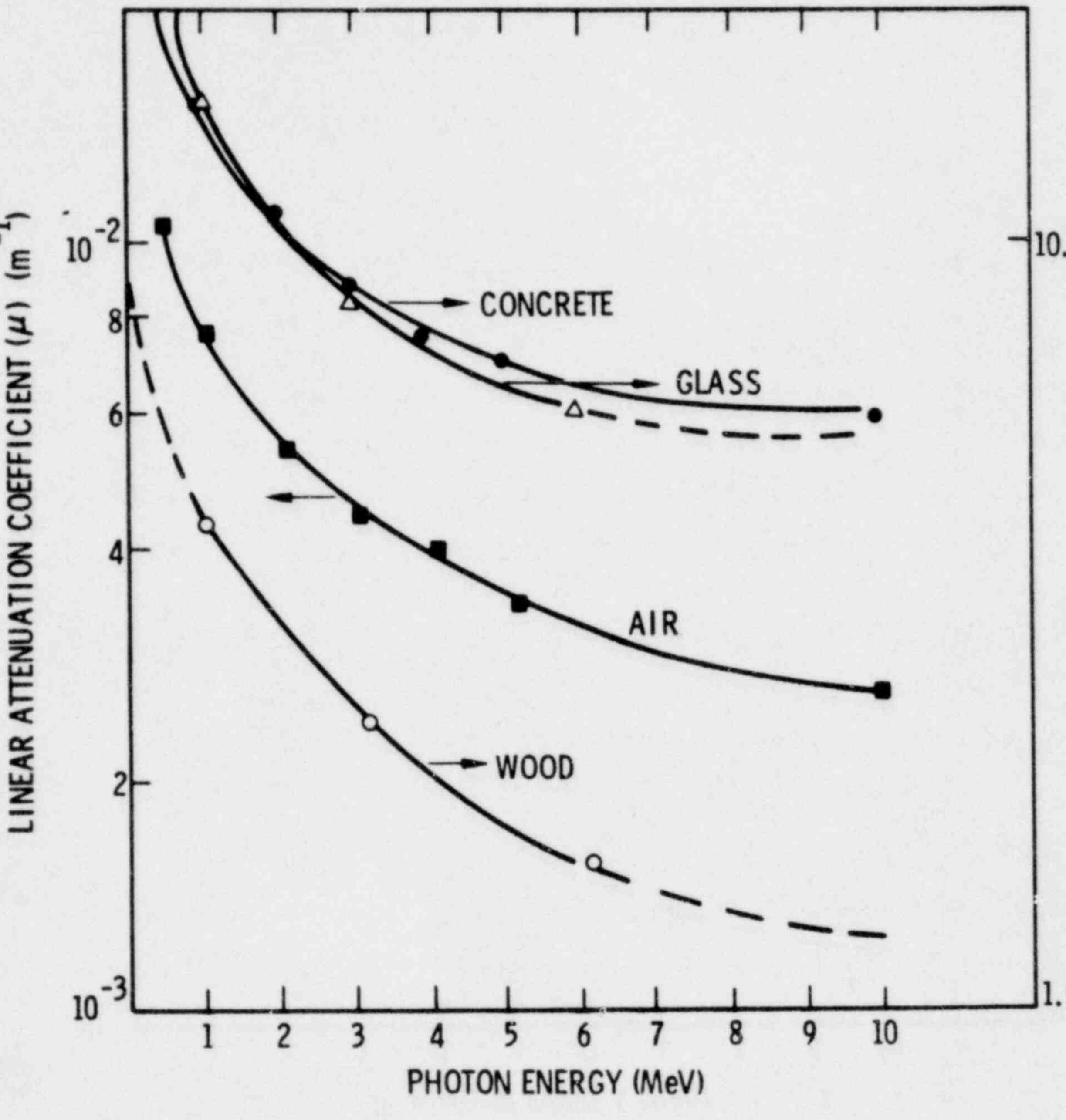


Figure 10. Linear Attenuation Coefficients as a Function of Energy for Some Materials

TABLE 1

ATTENUATION COEFFICIENTS FOR VARIOUS MATERIALS (m^{-1})

Photon Energy (MeV)	Air (a)	Concrete (b,c)	Wood (d,e)	Glass (d,f)
0.5	1.11×10^{-2}	22.	0.5*	22.*
1.0	0.81×10^{-2}	15.	0.4	15.
2.0	0.57×10^{-2}	11.	3.1*	10.5*
3.0	0.46×10^{-2}	8.8	2.5	8.6
4.0	0.41×10^{-2}	7.8	2.1*	7.4*
5.0	0.35×10^{-2}	7.1	1.8*	6.7*
6.0	0.32×10^{-2}*	6.6*	1.7	6.3
10.0	0.26×10^{-2}	6.0	1.25*	5.6*

(a) Source - Reference 8, Table 8.75.

(b) Source - References 7 and 8.

(c) The concrete mixture is Portland Cement: sand: gravel: 1:2:4.

(d) Source - Reference 7.

(e) The wood is an average of ash, oak, and white pine. The values are closest to that for white pine.

(f) Reference 7 for average plate glass.

*Obtained by interpolation using Figure 10.

where E = incident photon energy (MeV)

μ = attenuation coefficient (m^{-1}) (the product w_b is called relaxation length)

$A_1, A_2, \alpha_1, \alpha_2$ = empirical constants

w_b = thickness (m)

Reference 6 provides curves for A_1, A_2, α_1, and α_2 for some materials. The curves for concrete are included as Figure 11. Reference 5 provides buildup factor data for various types of glass for various relaxation lengths. Using type 8365 glass and $\mu w_b = 2$, buildup factors for thin barriers of glass can be estimated. Buildup factor information is not directly available for wood. However, a value can be approximated using a curve in Reference 7 (Figure 9.1.12-76). This figure gives a value of 1.31 for $\mu w_b = 1.68$. Another approach is to use a curve in Reference 9 for dose buildup factor as a function of atomic number (Z) for 4 MeV gamma radiation. If wood is assumed to be cellulose ($C_6H_{10}O_5$), with an average Z of 10 and if it is assumed that $x = 1.0$, a buildup factor of 1.5 would be appropriate. Since it is desirable to be conservative if significant variations exist, the value chosen for wood is 1.5 for all energies.

Reference 2 suggests a form for the buildup factor in air as

$$BF = 0.00197r + 1, \tag{18}$$

where r = distance (m).

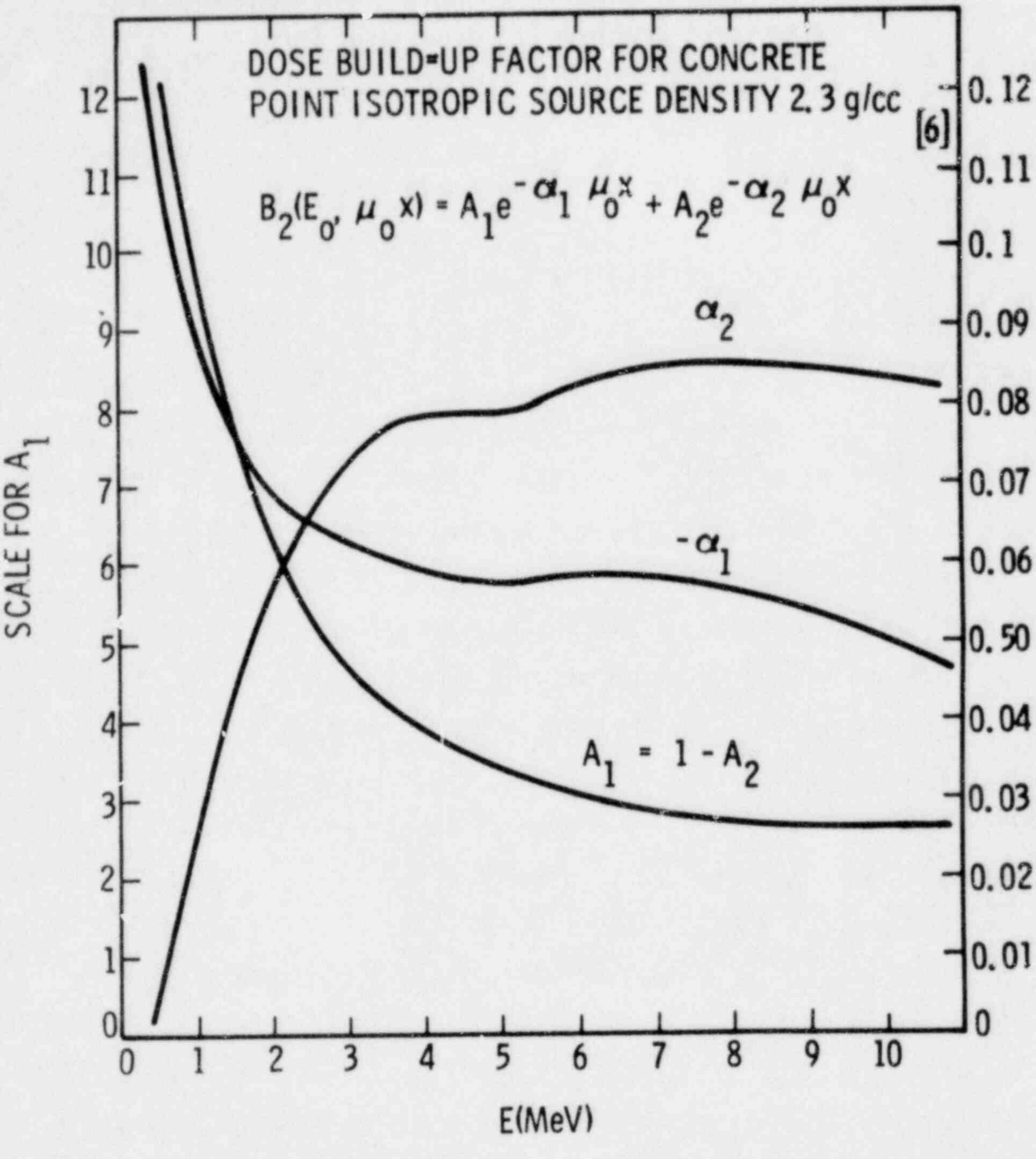


Figure 11. Dose Buildup Factor for Concrete

This is valid for gamma energies between .45 MeV and 4 MeV which encompass all electromagnetic radiation sources normally fixed during transport of radioactive materials.

Figure 12 shows a plot of buildup factor vs energy for the various materials.

Multiple Slab Geometry - A multiple slab geometry arises from the fact that the photon flux must penetrate a "slab" of air and then a "slab" of building material before it reaches the population of concern. (Note that package shielding and radiation type are accounted for by using TI, and that shielding due to vehicle materials or other packages is not included.) In this simplified model, therefore, the problem reduces to a two slab problem. Reference 6 suggests that where there are two slabs with a light material (i.e., air) followed by a heavier material (i.e., wall) it is most accurate to use the buildup factor for the heavier material alone, regardless of slab thickness. This is what is done in the model.

Obliqueness Factor - The assumption that radiation obliquely incident on a shield is attenuated as if it were normally incident on a shield of thickness equal to the effective slant distance may lead to significant dose underestimates because scattered radiation may play an important role. When radiation impinges perpendicularly on a shield, the scattered radiation which penetrates the shield, in all cases, travels farther in the shield than does the uncollided flux. This may not be the case with oblique incidence. Using a technique described in Reference 6, a factor can be derived for the buildup/attenuation tradeoff for oblique impingement. This is done by using

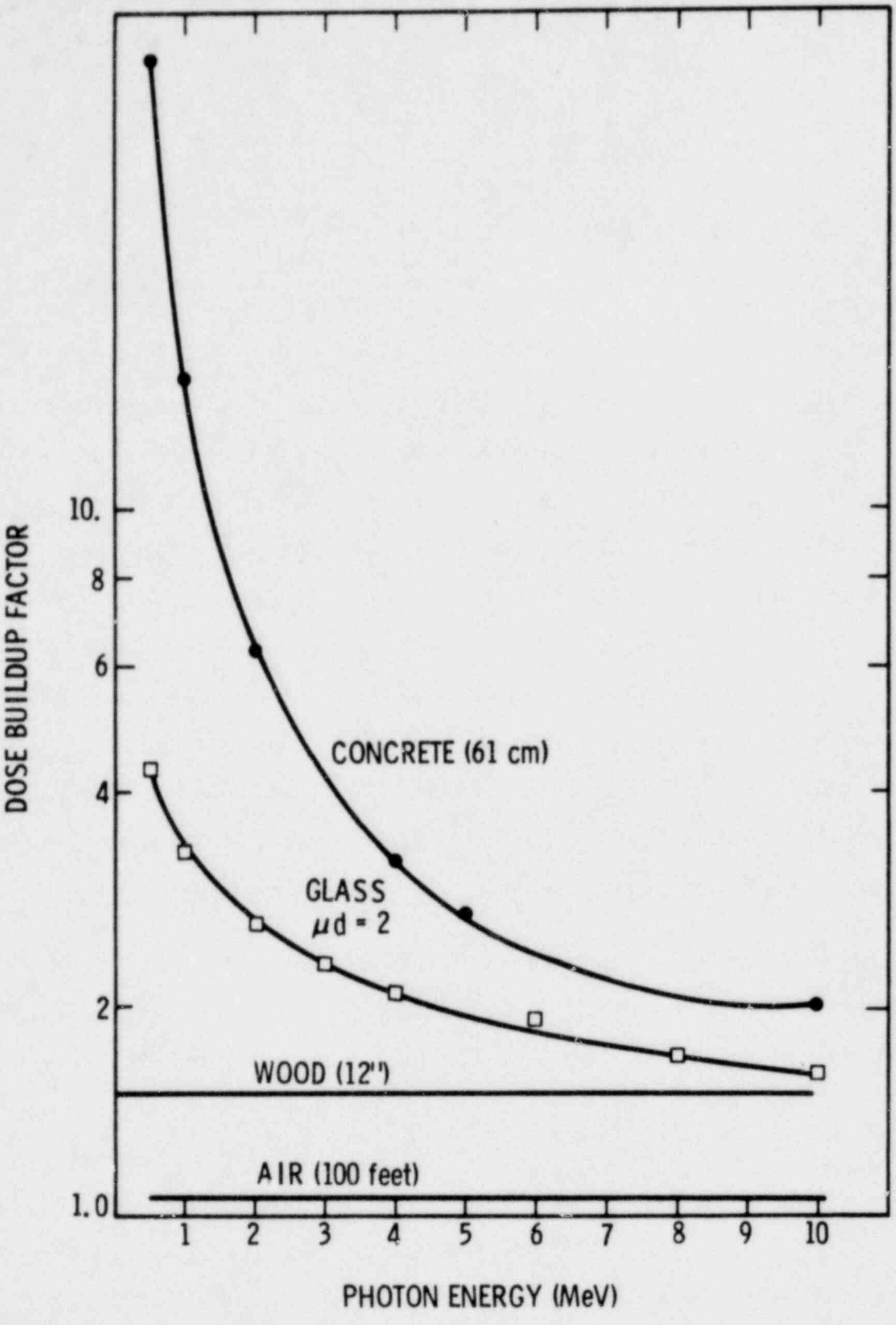


Figure 12. Dose Buildup Factors as a Function of Energy for Some Materials

by using the information in Figure 13 and normalizing the angle buildup factor to the straight-through buildup factor. This ratio is then applied to the perpendicular path dose expression to account for the oblique impingement. If it is assumed that multi-floor buildings are constructed using concrete, and that their average wall thickness is 24 inches, a value of 4.27 for relaxation length, (using μ for 6 MeV gamma rays to correspond to values used for Figure 13) is computed.* An "obliqueness correction factor" (OF) vs angle for this idealized multi-floor building can now be plotted as shown on Figure 14.

The angle between the center of a particular floor and a point in the center of the street directly in front of the building would be used if the vehicle always stayed in front of the building. In fact, the angle subtended by a ray-path must also account for the distance of the vehicle from the point directly in front of the building as shown in Figure 15. Based on this geometry, the oblique angle of impingement is given by

$$\theta = \tan^{-1}\left[\frac{\sqrt{(r')^2 + \{h(n-.5)\}^2}}{(w_{st/2} + w_s)}\right] , \tag{19}$$

while the slant distance from the vehicle to the point of oblique impingement is given by

$$r = \quad (r')^2 + \quad h(n-0.5) \quad ^2 + ({}^{W}st/_2 + W_s)^2 \quad . \tag{20}$$

*The value of 6 MeV was chosen based on available data for oblique impingement of photons. Since the angular adjustments given in Figure 13 are ratioed to the straight through path, the fact that 6 MeV radiation is used should not introduce a significant error.

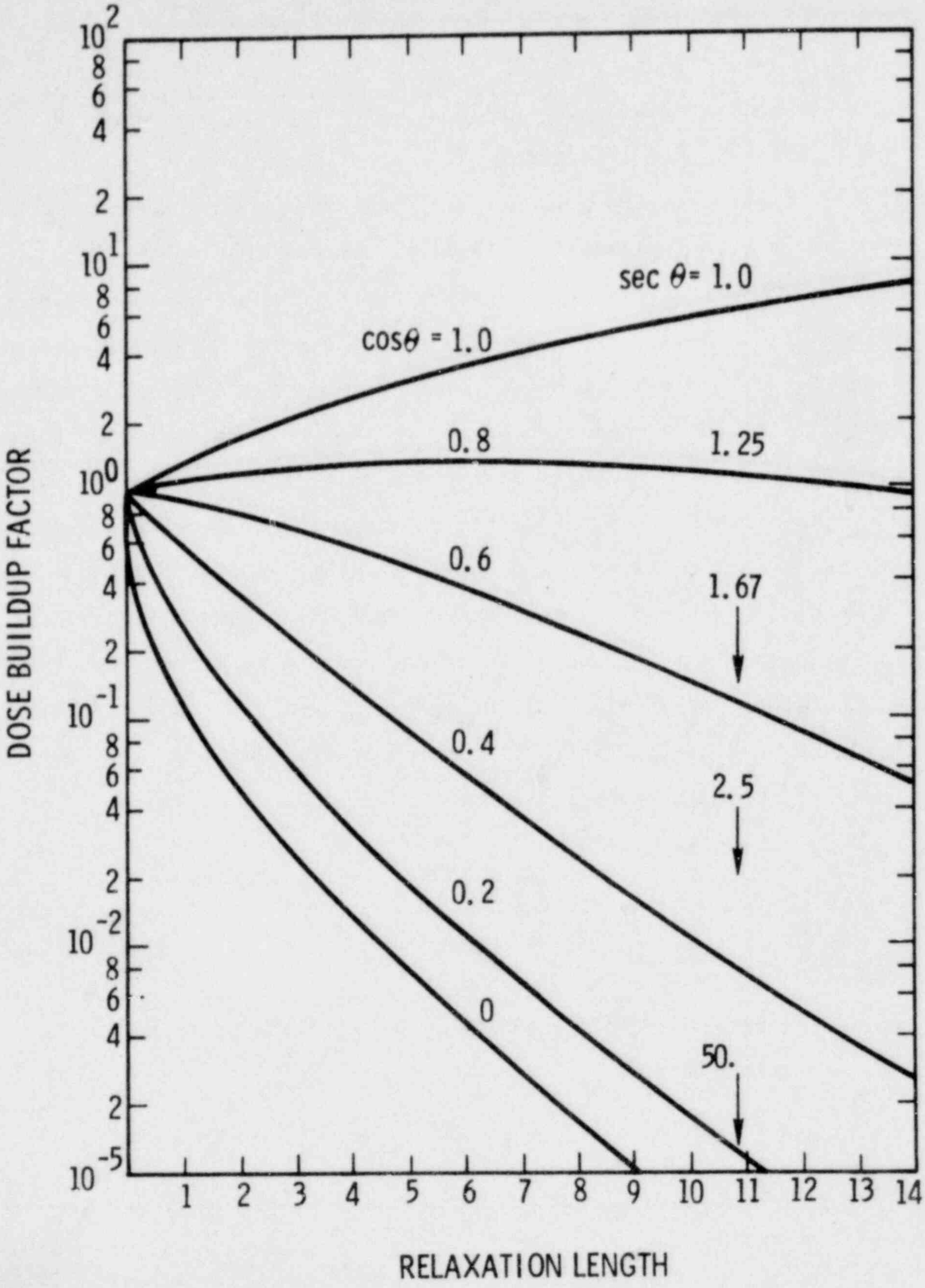


Figure 13. Peebles Buildup Factor (Iron Buildup Used)

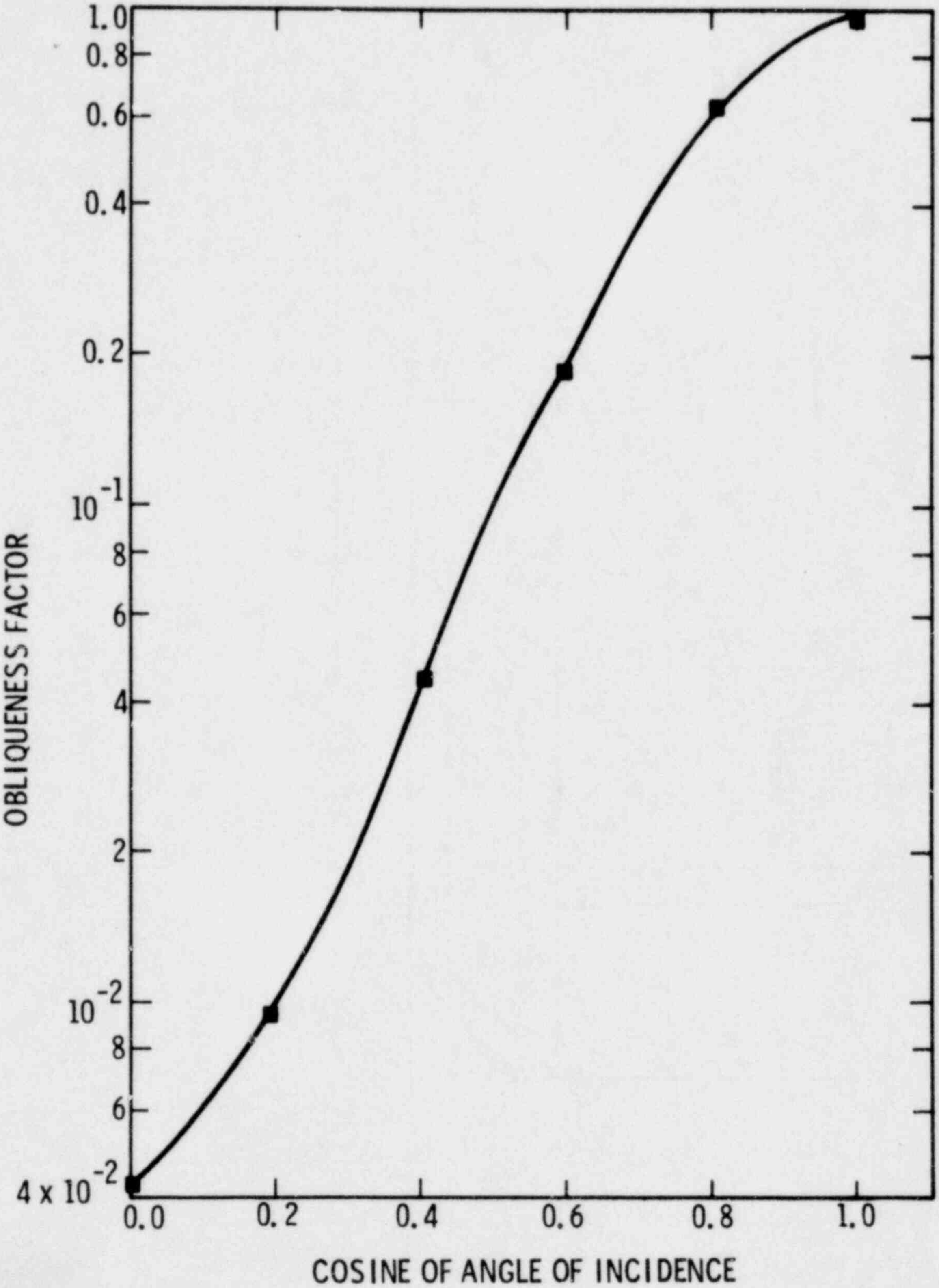


Figure 14. Obliqueness Factor

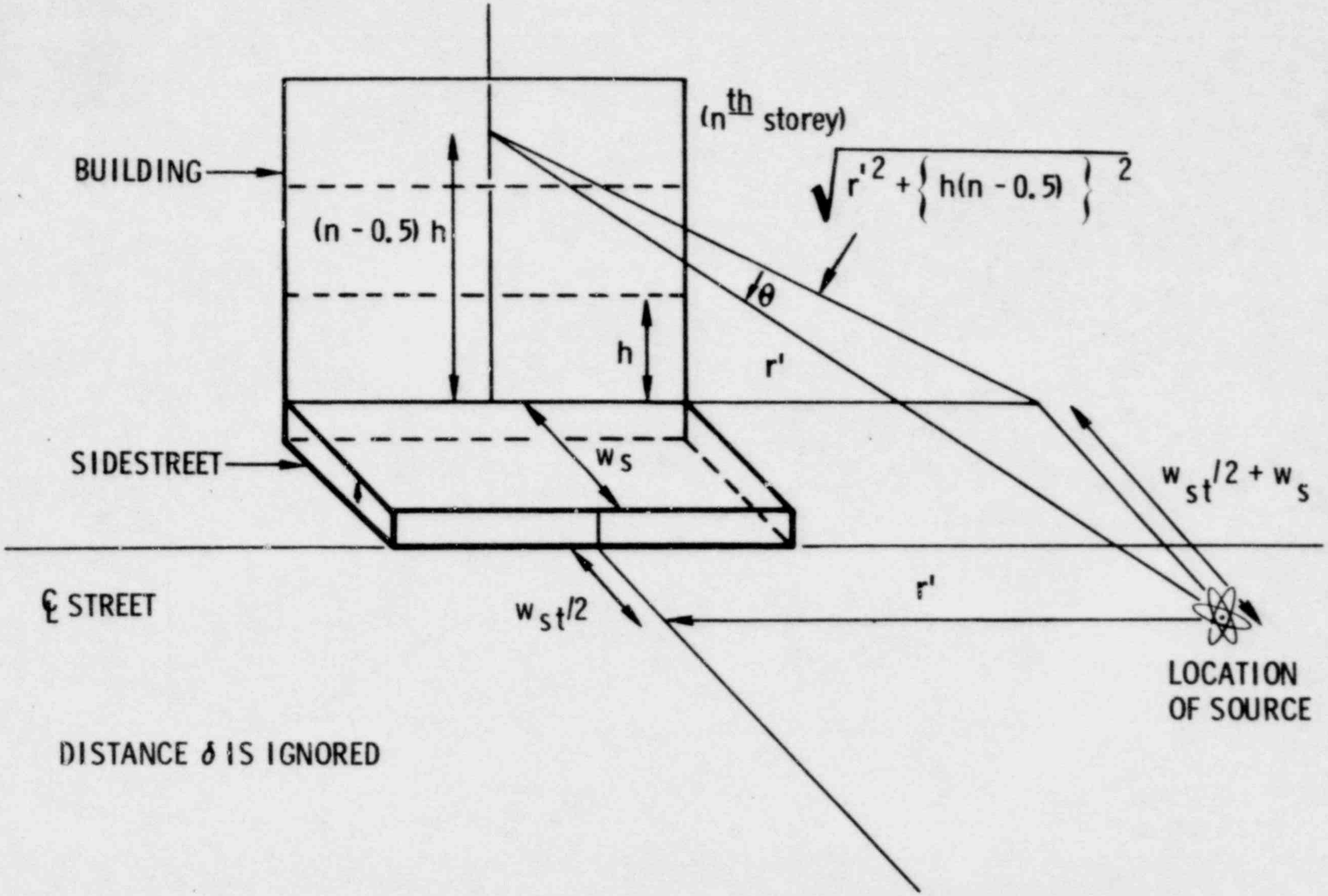


Figure 15. Obliqueness Geometry

It can be shown that the obliqueness factor plotted in Figure 14 can be replotted as a function of slant distance r. The result is a family of curves for various values of the sum $w_{st/2} + w_s$ which provides the values for obliqueness factors used in the computations.

Before these radiological factors can be translated into a population dose model, the distribution of people within the buildings must be established. The number of people in buildings is computed from Census Bureau data for worker flux from home to work[10] and from estimates of the number of trips made for various other purposes.[11,12] The assumption is made that all people who are residents, workers, or transient clientele are inside buildings. This is a conservative assumption since some of them are clearly accounted for in the estimates of pedestrian density and people in vehicles. The expression used to calculate the number of people in buildings is given by:

$$PPB = (PD * A) + (TC * A), \tag{21}$$

where

PPB = persons inside buildings in cell

PD = overall population density in cell (residents $\pm$ commuters) (persons/km^2)

A = area of cell (km^2)

TC = number of transient clientele (persons/km^2).

If it is assumed that people are uniformly distributed on a floor-by-floor basis, the number of people per floor is given by

$$PPF = \frac{PPB}{n}, \tag{22}$$

where

n = number of floors for buildings in cell.

The actual ray-path geometry can be extremely complicated, as shown on Figure 16. Radiation can pass directly through building materials or can have multiple scatterings in air, windows, or wall materials. In order to account for the population distribution on each floor and the nonhomogeneity of the outer wall, it is assumed that all people are immediately adjacent to the inside of the outer wall of the building. In addition to this assumption, the fact that no allowance is made for shielding due to interior partitions, inside furnishings, or floor materials, makes the analysis conservative.

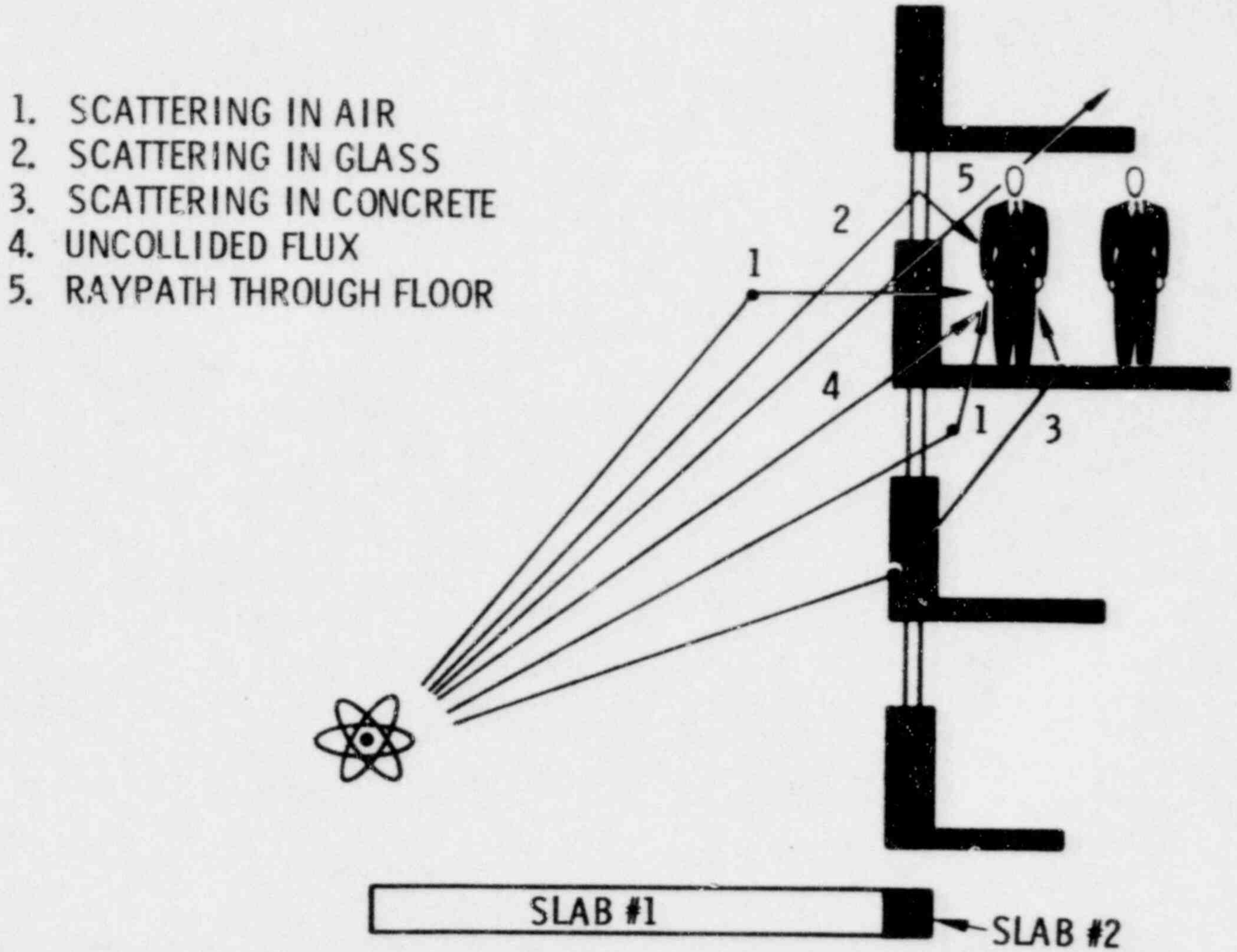


Figure 16. Ray-paths to People in Buildings

Using the same integration techniques used in Equation 6 for determining dose to a person at a fixed distance as a source passes by, and incorporating the population distribution and radiological factors discussed above, the following expression for the integrated population dose to people in buildings on both sides of the street due to a single shipment through a specific cell can be derived:

$$ID = \sum_{i=1}^{n} \left\{ \frac{Q_1 * 2 * K_o * TI * PPS}{\bar{v}} * PPF * \frac{L * w_{st}}{A * f_{st}} * \right.$$

$$\left. e^{-\mu_b w_b} * B_b(w_b) * \int_{\beta_1}^{\infty} \frac{e^{-\mu_{air} r} * OF_i(r)dr}{r\left[r^2 - \left(\sqrt{\{h(i-.5)\}^2 + (w_{st}/_2 + w_s)^2}\right)\right]^{1/2}} \right\} , \quad (23)$$

where i = variable over floors

$$\beta_1 = \sqrt{\{n(i-.5)\}^2 + \{w_{st}/2 + w_s\}^2}$$

Note that this assumes that the shipment moves from $+\infty$ to $-\infty$ exposing people. This approximates the condition where people in one cell may receive some dose while the source is in an adjacent cell.

˜.4 People in Vehicles

As a transport vehicle moves along a transport link, people in vehicles sharing the link with the shipment are exposed to external penetrating radiation from the package. As shown in Figure 17, there are two subgroups of persons who may be exposed: persons in vehicles moving in the same direction as the shipment, and persons in vehicles moving in the direction opposite to the shipment. The dose to people moving at right angles to the shipment can be shown to be negligible using arguments similar to those used to dispense with dose received by pedestrians moving perpendicular to the shipment direction.

The model for dose to people moving in the same direction as the shipment assumes that the transport vehicle is moving at about the same average velocity as the rest of the traffic between intersections. Under this assumption, traffic can be modeled as a stationary set of vehicles with some specific intervehicle distance, d_1, lined up ahead of and behind the shipment vehicle. Depending upon traffic conditions, the transport vehicle will stop at some or all of the intersections along its route. When traffic stops under these circumstances, it can again be modeled as a stationary set of vehicles at some shorter separation distance, δ.

In addition, the following assumptions are made:

1) Vehicles accelerate to cruising speed and decelerate instantaneously.
2) The separation distance changes from d_1 to instantaneously.

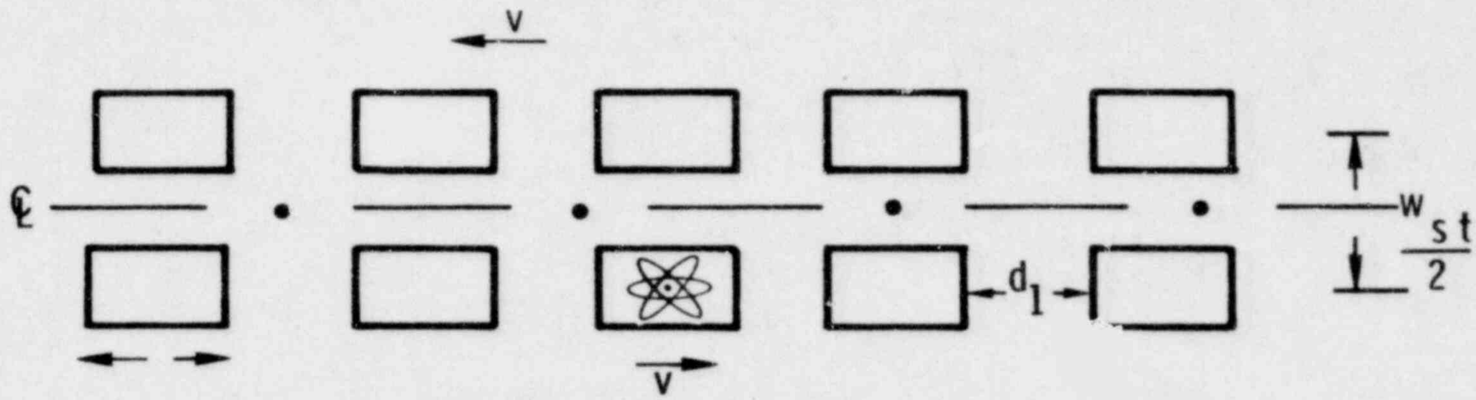


Figure 17. Accident-free Dose to People in Vehicles

3) The line of vehicles ahead of and behind the shipment vehicle extends infinitely in both directions.

4) No shielding is provided by vehicles.

5) Exposed persons are at the center of vehicles.

6) Traffic is uniform across lanes on each side of street.

Using these assumptions, a 4-block example, as shown in Figure 18, can be developed. This figure shows the vehicle stopping at half of the intersections. Thus the total integrated dose to persons at a distance d_1 from the vehicle during the <u>cruising</u> phase is given by

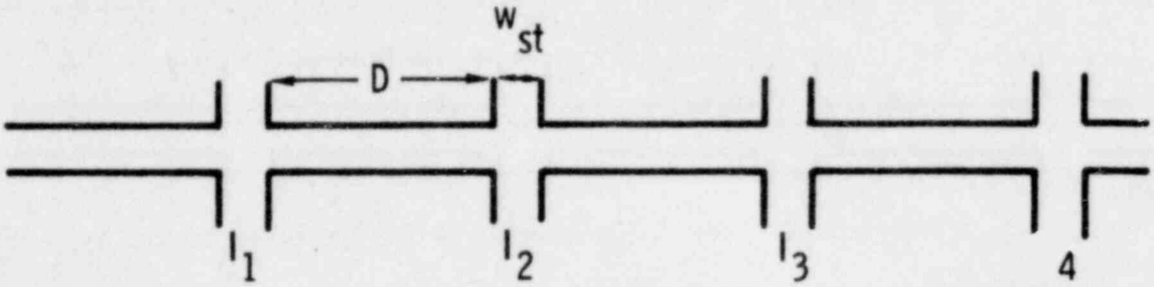
$$ID_c(d_1) = K * \frac{e^{-\mu(d_1+\ell)}}{(d_1+\ell)^2} * \frac{4(D' + w_{st})}{V_c} \quad . \tag{24}$$

The general form of Equation 24 for a single infinite line of vehicles centered on the shipment vehicle which gives the total integrated dose during the cruising phase can be similarly derived:

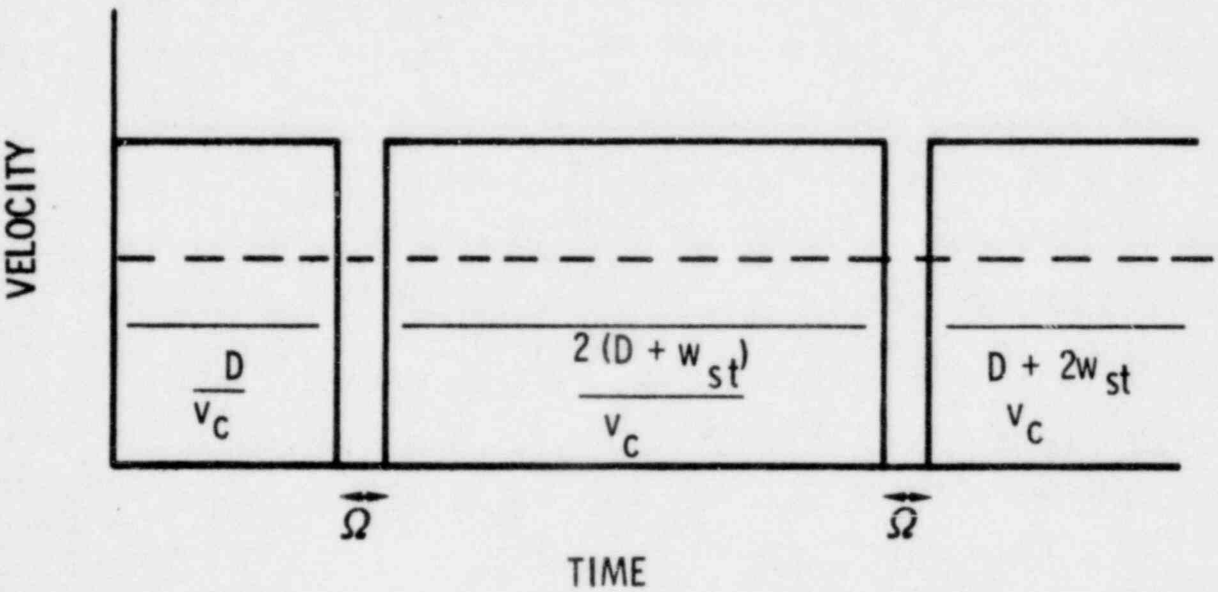
$$ID_c = 2 * K * \frac{4(D' + w_{st})}{V_c} * \sum_{j=1}^{\infty} \frac{e^{-\mu(d_1+\ell)j}}{\left[(d_1+\ell)j\right]^2} \quad . \tag{25}$$

The dose delivered during the stopped phase can be developed analogously:

$$ID_{stopped} = K * 2\Omega * \sum_{j=1}^{\infty} \frac{e^{-\mu^{(\delta+\ell)}j}}{\left[(\delta+\ell)j\right]^2} \quad , \tag{26}$$



VEHICLE STOPS AT I_1 AND I_3 AND DRIVES THROUGH I_2 AND I_4



v_c = CRUISE VELOCITY

Ω = TIME STOPPED AT INTERSECTION

v = AVERAGE VELOCITY = $\dfrac{4(D + w_{st})}{\dfrac{4(D + w_{st})}{v_c} + 2}$

Figure 18. Sample 4-block Route

where Ω = stop time at intersection. It can be shown that, for all values of μ, $(d_1 + \ell)$ and $(\delta + \ell)$, $e^{-(xxx)j} \leq 1.0$. This assumption reduces the summation to the summation of the inverses of the squares of all integers which can be shown to be equal to $(\pi/8 + \pi/24)$.[13] Use of this value in place of the actual exponential summation overestimates the actual dose by approximately 7%.

In order to more accurately model dose to people in vehicles, a phenomemon called "bunching" must be considered. This occurs when vehicles cluster or bunch up at intersections. It can be shown that virtually all of the dose to people in vehicles is accumulated by persons in the first three vehicles adjacent linearly in all directions from the shipment. With this in mind, the intersection situation can be visualized as shown in Figure 19. Using Equation 26, the dose absorbed by people in vehicles at the intersection can be expressed as

$$ID_{stopped} = \frac{K * f * \xi \, L \, \Omega}{D' \, (\delta + \ell)^2} \, , \qquad (27)$$

where $f \leq 10.28$ allowing for the dose to each "circle" of vehicles to be considered separately) with a maximum of 36 vehicles at risk. There may be certain conditions under which the traffic will be light enough that fewer than this number will be available. If it is assumed that all the vehicles proceeding one way with the shipment along a street bunch at each intersection, the number of vehicles which will collect at any intersection is given by

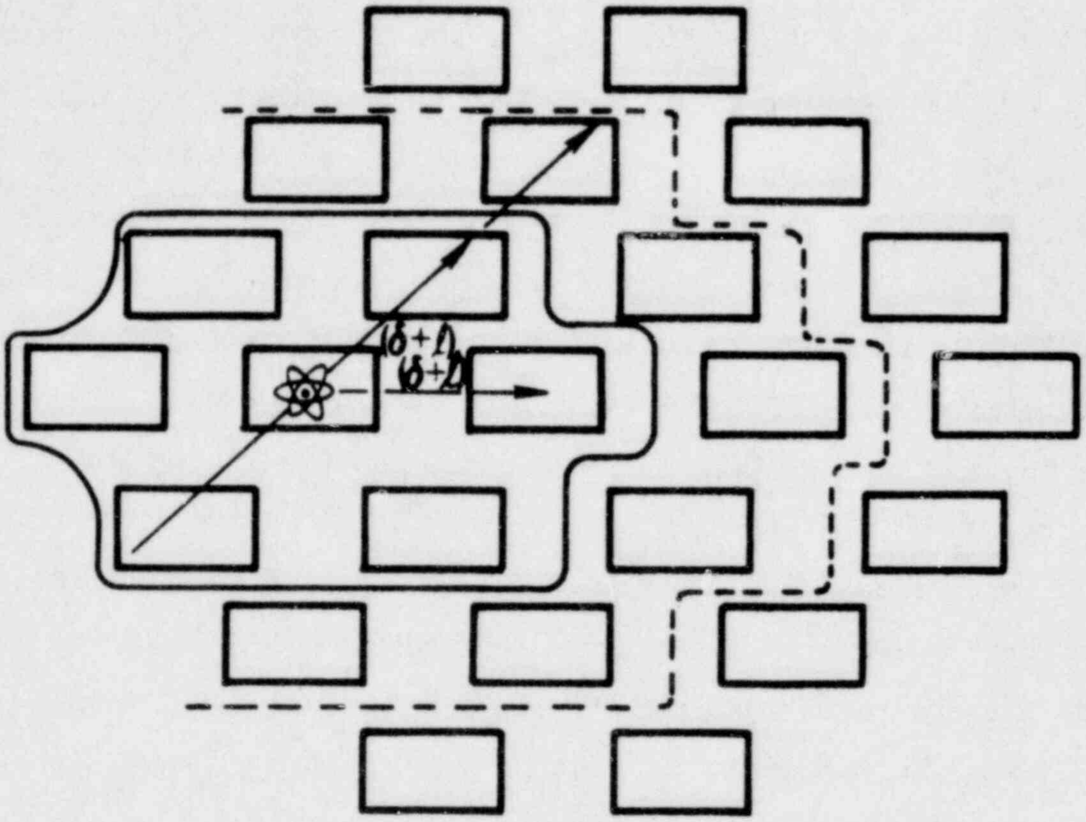


Figure 19. Model of Dose to People in Vehicles Including the Phenomenon of Intersection Bunching

$$\text{Vehicles per block (one way)} = \frac{N*D'}{Q_2*\bar{V}} \tag{28}$$

where N = hourly one-way traffic count

$\bar{V}$ = average velocity (m/sec)

D' = block length (m).

This effect is incorporated by testing the number of "bunched" vehicles against the maximum number of dosimetrically significant vehicles (i.e., 36). The f in Equation 27 is modified as shown in Table 2, depending on the value obtained for vehicles per block.

This model is also conservative in that it assumes that the shipment vehicle is always at the center of the cluster, and that all the available vehicles on the block are clustered around the shipment for the entire stopped period.

By incorporating these assumptions into the cruising phase, and by generalizing the fraction of intersections at which the vehicle must stop (ξ), the final form used to compute the "same direction dose" is obtained:

$$ID \le \frac{1}{Q_2} * K * f \left[\frac{2*L}{V_c(d_1+\ell)^2} + \frac{Q_7 \xi L \Omega}{D' (\xi+\ell)^2} \right] \quad . \tag{29}$$

The model for dose to people moving in the direction opposite to the shipment is based on the integrated dose relationship for a person as a shipment moves past him from $-\infty$ to $+\infty$ (Figure 4 and Equation 6).

TABLE 2

Vehicles per Block (Eq. 28)	f	Maximum Possible Dose (%)
≥ 36	10.28	100
18-35	8.52	83
7-17	7.52	73
6	5.76	56
5	4.8	47
4	3.84	37
3	2.88	28
2	1.92	19
1	0.96	9
1	0	(no adjacent vehicles)

If it is assumed that traffic velocity is the same in both directions, as indicated in Figure 17, persons traveling in the opposite direction can be modeled as stationary with the shipment passing by at a speed of $2V_c$. By noting that the linear population density can be specified by

$$LPD = \frac{N}{Q_2 * V_c} * PPV, \tag{30}$$

that the separation distance is $w_{st}/2$ (half of the street width), and that the total exposure time in each cell is given by L/V_c, the integrated dose to people moving opposite to the shipment can be expressed as

$$ID_{O.D.} = 2 * K * \frac{L}{V_c} * \frac{N}{V_c} * PPV * Q_3 * \int_{w_{st/2}}^{\infty} \frac{e^{-\mu_{air} r} B_{air}(r)dr}{r(r^2 - \left[w_{st/2}\right]^2)^{1/2}} . \tag{31}$$

By combining Equations 29 and 31 the following expression for dose to people in vehicles sharing the transport link with the transport vehicle can be obtained:

$$ID = K_o * TI * PPS * PPV * Q_4 *$$

$$\left\{ f\left[\frac{2*L*}{V_c(d_1 + \ell)^2} + \frac{Q_7 \ell \Omega L}{D'(\delta + \ell)^2}\right] + \right. \tag{32}$$

$$\left. \left[\frac{*L*N}{Q_2 * V_c^2} * \int_{w_{st/2}}^{\infty} \frac{e^{-\mu_{air} r} B_{air}(r)dr}{r\left[r^2 - (w_{st/2})^2\right]^{1/2}}\right] \right\} .$$

2.5 Crewmen

Crewmen aboard a vehicle transporting radioactive material will be exposed to external penetrating radiation, at some low level for the duration of their trip. If a characteristic source-to-crew distance, d_2, is assigned for the particular mode, an expression for the dose received by the crewmen during a transit through a cell can be written:

$$ID_{crew} = Q_4 * \frac{L}{\overline{V}} * N_c * \frac{K_o *TI*PPS*e^{-\mu_{air} d_2} *B_{air}(d_2)}{d_2^2} \quad . \tag{33}$$

where $L/\overline{V}$ = length of time of exposure

N_c = number of crewmen.

Note that this development assumes no shielding from structural portions of the vehicle, or from other cargo in the vehicle. Since transport vehicle materials and construction vary widely, from vehicles with shielded cabs to delivery vans with no partition between driver and source, and since cargo distribution schemes can also vary considerably, the conservative assumption of no vehicle shielding for crewmen is made. This approach is supported by a tabulation of shielding factors in Reference 14 which shows that vehicles provide negligible shielding from gamma radiation due to a cloud of airborne radioactive material.*

*In the case of exclusive use vehicles, the dose rate in any continously occupied portion of the vehicle (i.e., the cab) is limited by law to 2 mrem/hr. The model limits the cab dose rate to this value.

2.6 Modifications to Account for One-Way Streets and Freeways

The model development thus far assumes bidirectional street travel. In actual fact, urban traffic patterns frequently involve considerable use of one-way streets and/or limited-access freeways. Travel on roadways of this type will modify the preceding analysis as follows.

2.6.1 One-Way Streets

If it is assumed that vehicles on one-way streets are traveling at the center of the street, two equations must be modified. The dose to pedestrians given in Equation 9 becomes

$$ID = Q_1 * PedD * L * (2*K_o*TI*PPS)* \frac{L*w_{st}}{A*f_s} * ABD *$$

$$\left[\frac{1}{\overline{V}+v_p} + \frac{1}{\overline{V}-v_p}\right] * \int_{0.5\,w_{st}}^{0.5\,w_{st}+w_s} I(x)\,dx \quad , \tag{34}$$

and the dose to people in vehicles (Equation 32) becomes

$$ID = Q_4 * K_o * TI * PPS * PPV * f *$$

$$\left[\frac{L}{V_c(d_1+\ell)^2} + \frac{Q_7 * \ell * \Omega * L}{D'\,(\delta+\ell)^2}\right] \quad . \tag{35}$$

The dose to people traveling in the opposite direction is automatically zero and the formulations for dose to people in buildings and dose to crew remain unaffected.

2.6.2 Freeways

Four dose expressions must be modified to allow for vehicle travel on freeways: first, pedestrian dose is set to zero; second, dose to crew is modified by substituting freeway velocity, V_f, for average velocity, $\bar{V}$, in Equation 33; third, the dose to people in vehicles (Equation 32) is modified as follows:

$$ID = Q_4 * K_o * TI * PPS * PPV *$$

$$\left\{ \left[f_f * \frac{L}{V_f (d_1^f + \ell)^2} \right] + \left[\frac{Q_4 * L * N_f}{V_f^2} * \int_{w_f}^{\infty} \frac{e^{-\mu r} B(r) dr}{r (r^2 - w_f^2)^{1/2}} \right] \right\} , \qquad (36)$$

where f_f = bunching factor for freeways (computed similarly to f in Equation 32 using corresponding values for freeways)

V_f = average freeway velocity (m/sec)

d_i = average freeway separation distance (m)

N_f = average freeway traffic count

w_f = centerline-to-centerline freeway width (m).

Fourth, the dose to people in buildings (Equation 23) is modified as follows:

$$\mathrm{ID} = \sum_{i=1}^{n} \left\{ \frac{Q_1 * 2 * k_o * \mathrm{TI} * \mathrm{PPS}}{V_f} * \mathrm{PPF} * \frac{L * w_f}{A * f_{st}} * \right.$$

$$^{-\mu_b w_b} * B_b(w_b) * \left[\int_{\beta_2}^{\infty} \frac{e^{-\mu r} \mathrm{OF}_i(r)\,dr}{r\left(r^2 - \beta_2^2\right)^{1/2}} + \right. \tag{37}$$

$$\left. \left. \int_{\beta_3}^{\infty} \frac{e^{-r} * \mathrm{OF}_i(r)\,dr}{r\left(r^2 - \beta_3^2\right)^{1/2}} \right] \right\} \quad .$$

where

$$\beta_2 = \sqrt{\left\{h(i - .5\right\}^2 + \left(\frac{w_f}{2}\right)^2}$$

$$\beta_3 = \sqrt{\left\{h(i - .5)\right\}^2 + \left(\frac{1.5 w_f}{2}\right)^2} \quad .$$

3. Accident-Free Dose Due to Rail Transport

Accident-free dose due to transport of radioactive material by rail is similar to the truck development described earlier, with four important differences:

1) Since sidewalks are not situated along railroad tracks, dose to pedestrians is not explictly computed.
2) Since freight trains may pass through or stop in passenger terminal areas, a "Depot Dose" is calculated.
3) Because of the large amounts of massive shielding between crew and source in the form of engines, cars, etc., crew dose is considered neglible.
4) Because trains may pass through areas containing people in buildings, people in vehicles, and pedestrians, a "Right-of-Way Dose" is computed.

3.1 Dose Accumulated in Railroad Terminals

If the populated terminal area is modeled as an annular area with no one closer to the package than some distance, r_1, and with people uniformly distributed between that radius and some maximum radius, r_2, Equation 2 can be integrated using an annular differential element to yield the following expression for integrated dose:

$$ID = Q_5 * K_o * TI * PPS * T_{Depot} * PD_{Depot} * \int_{r_1}^{r_2} \frac{(2\pi r)e^{-\mu_{air} r} B_{air}(r)dr}{r^2} , \quad (38)$$

where

T_{depot} = average stop time in depot area (hr)

PD_{depot} = population density in depot area (persons/km^2)

r_1 = minimum radius (m)

r_2 = maximum radius (m).

3.2 Persons Sharing the Transport Link

Although commercial passenger trains are disappearing on a national level, many urban areas still have extensive commuter rail service to suburban areas, so some population exposure can be accumulated by people in these trains. The development and assumptions are similar to those for dose to people in vehicles traveling in the direction opposite to the s ment (Equation 31). When factors appropriate to rail transport are substituted, the expression becomes

$$ID = 2 * Q_3 * K_o * TI * PPS * \frac{L*N_T}{{V_T}^2} * PPT * \int_{r_3}^{\infty} \frac{e^{-\mu_{air} r} B_{air}(r) dr}{r\left[r^2 - r_3^2\right]^{1/2}} , \tag{39}$$

where

N_T = train traffic count (vehicles/hr)

V_T = average train velocity (m/sec)

PPT = number of persons per train

r_3 = distance between passing trains (m).

3.3 Persons Along the Right-of-Way

The location of railroad tracks in relationship to streets, buildings, and pedestrian areas is highly variable. Therefore, an average value for person density along the railroad right-of-way is computed using the average overall population density given by

$$PD_{Rw} = PD + TC + PedD + \left[\frac{N*PPV}{Q_2*\bar{V}}\right] . \tag{40}$$

This expression can be combined with a form similar to Equation 8 to compute the integrated dose along the right-of-way.

$$ID = 4 * Q_1 * PD_{Rw} * K_o * TI * PPS * \frac{L*2R_w}{A} * \frac{L}{V_T} * \int_{R_w}^{\infty} I(x)dx \ , \tag{41}$$

where

PD_{Rw} = value given in Equation 40

R_w = right-of-way distance (m)

$$I(x) = \frac{e^{-\ r}B(r)dr}{r(r^2-x^2)^{1/2}} . \tag{41a}$$

Note that no shielding is considered and no obliqueness effects are included for people in buildings.

4. Accident-Free Dose Due to Air Transport

Two different types of air transport are considered from an accident-free dose perspective: dose due to passenger aircraft service, and dose due to cargo aircraft service. In both cases only the dose to people in the terminal area is considered applicable to the urban area alone. The dose accumulated by crewmen, flight attendants, or on-board passengers has been previously evaluated[3] and will not be repeated in this study.

The fundamental mathematical form for dose to persons in terminals is that derived for rail depot doses in Equation 38. By substituting air parameters for the rail parameters, the following expression is obtained:

$$ID = Q_5 * K_o * TI * PPS * \Delta T_{Term} * PD_{Term}$$

$$\int_{r_4}^{r_5} \frac{(2\pi r)e^{-\mu_{air} r} B(r)dr}{r^2}, \qquad (42)$$

where

T_{Term} = the average stop time in air terminals (hr) (different for passenger and cargo aircraft)

PD_{Term} = terminal area population density (persons/km^2) (different for passenger and cargo aircraft)

r_4 = minimum radius (m)

r_5 = maximum radius (m).

5. Accident-Free Dose Due to Water Transport

Like air transport, the urban component of transport by water is principally accumulated in the locality where the vehicle stops, i.e., the dock area. Ships and barges are massive steel structures, and shipping lanes in navigable rivers are generally centered in the channel at long distances from shore. Therefore, neither crewmen nor people along the riverbank would receive appreciable doses. The dose received by persons in the dock area is developed similarly to that for rail depots and air terminals with appropriate changes of nomenclature:

$$ID = 0.5 * Q_5 * K_o * TI * PPS * T_{dock} * PD_{dock} *$$

$$\int_{r_6}^{r_7} \frac{(2\pi r) e^{-\mu r} B(r) dr}{r^2} , \qquad (43)$$

where

T_{dock} = time spent in dock area (hr)

PD_{dock} = person-density in dock area (persons/km^2)

r_6 = minimum exposure radius (m)

r_7 = maximum exposure radius (m).

Note that a factor of 0.5 is included since half of the annular area around the vessel will be open water.

6. Accident-Free Dose to Handlers and Warehousemen

Two population subgroups receive an accident-free dose independent of the mode of transport. These two subgroups are handlers and warehousemen.

6.1 Accident-free Dose to Handlers

The expression for dose to handlers is based on previous assessments of package handling:[9,15,16] one which considers the handling of small packages and one which considers the handling of large packages such as casks, etc.

A study was conducted on the handling of small radioactive packages by cargo handlers at airport freight terminals.[15]
Using this study, the dose to cargo handlers can be specified as:

$$ID_H = Q_6 * N_H * PPS * TI, \tag{44}$$

where

ID_H = integrated dose to handlers per shipment (person-rem)

N_H = number of handlings

Q_6 = empirically-derived constant (person-rem/handling/TI).

In the case of casks, a general formulation based on References 2 and 16 is used. It is assumed that a person handling a large cask will probably be in close proximity to the radioactive source only while attaching or detaching rigging equipment or otherwise preparing the cask for the actual transfer operation. Since the radiation field around a large cask may be nonhomogeneous, particularly close to the cask, a dose rate based on some standard (such as a spent fuel cask) is used. Additionally, there may be a wide variation in handling capability for a particular cask at a particular location, so a standard handling time period is chosen. Two other variables must also be included: the number of handlers, and the number of transfer evolutions per shipment. Combining all these factors, the following general expression is obtained

$$ID_H = K_1 * K_2 * K_3 * K_4, \tag{45}$$

where

K_1 = dose rate at 3 feet from cask (e.g., .1 rem/hr)

K_2 = length of time spent in dose field (e.g., .5 hr)

K_3 = number of handlers required (e.g., 2)

K_4 = number of transfers per shipment (e.g., 1.0)

It should be noted that large casks, especially those containing irradiated fuel, are not expected to be handled in urban areas.

6.2 Dose to Warehousemen

If a radioactive package is placed in storage during a shipment, the warehouse personnel (other than handlers, who have been previously discussed) will be exposed to radiation from the package during their normal routine. If it is assumed that the package is stored so that no one (except handlers) will get within a certain exclusion radius, r_8, of the package, and that the warehouse personnel are distributed uniformly throughout the warehouse to some maximum radius, r_9, at some density, PD_{stor}, the integrated dose received during storage can be predicted by integrating a form of Equation 2 using an annular differential element as discussed earlier.

$$ID_{stor} = Q_5 * K_o * TI * PPS * \Delta T_{stor} * PD_{stor} * \int_{r_8}^{r_9} \frac{(2\pi r) e^{-\mu_{air} r} B_{air}(r) dr}{r^2} \tag{46}$$

where T_{stor} = storage time (hr).

Note that no credit is taken for shielding due to other stored items or internal warehouse structural materials.

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ADDENDUM 1

Variables, Constants, and Functions Used in Appendix D

APPENDIX D: Addendum 1

Evaluation of Integrals

I. Consider

$$\int_c^\infty \frac{e^{-\mu s}\, OF\left(\frac{w_{st}}{2} + w_s\, ,\, \theta\right) ds}{s\left(s^2 - c^2\right)^{1/2}} \, , \tag{1}$$

where

$$c = \sqrt{\left(\frac{w_{st}}{2} + w_s\right)^2 + \left[h\left(n - .5\right)\right]^2} \, , \tag{2}$$

$$s = \sqrt{r^2 + \left(\frac{w_{st}}{2} + w_s\right)^2 + \left[h\left(n - .5\right)\right]^2} \, , \tag{3}$$

and

$$\theta = \tan^{-1}\left(\frac{\sqrt{r^2 + \left[h\left(n - .5\right)\right]^2}}{\left(\frac{w_{st}}{2} + w_s\right)}\right) . \tag{4}$$

In order to remove the singularity at $s = c$, the substitution $s = c \cosh t$ is made:

$$\frac{1}{c}\int_0^\infty \frac{e^{-\mu c \cosh t}\; OF\left(\frac{w_{st}}{2} + w_s\, ,\; \theta(t)\right)\, dt}{\cosh t} \, . \tag{5}$$

A curve fitting routine is used to obtain a B-spline representation of OF vs θ. The numerical integration of the above integral uses GAUS8,[1] an adaptive routine based on the 8-point Gauss-Legendre formula:

1. Compute θ_c:

$$\theta_c = \tan^{-1}\left(\frac{h(n - .5)}{\frac{w_{st}}{2} + w_s}\right) , \tag{6}$$

(when $s = c$, $r = 0$ per Equations 2 and 3 above).

2. Locate θ_i, where θ_i is the first spline fit knot $> \theta_c$

3. Compute r_j's for θ_j's, $j \geq i$:

$$r_j = \sqrt{\left[\left(\frac{w_{st}}{2} + w_s\right) \tan \theta_j\right]^2 - \left[h(n - .5)\right]^2} . \tag{7}$$

4. Compute s_j's from r_j's:

$$s_j = \sqrt{r_j^2 + \left(\frac{w_{st}}{2} + w_s\right)^2 + \left[h(n - .5)\right]^2} , \tag{8}$$

or

$$s_j = \left(\frac{w_{st}}{2} + w_s\right) \sec \theta_j . \tag{9}$$

5. Determine t based on s value:

$$\text{Since } \cosh t = \frac{s}{c} , \quad \text{let } D = \frac{s}{c} , \tag{10}$$

$$\text{then } \frac{e^t + e^{-t}}{2} = D . \tag{11}$$

$$e^{2t} - 2De^t + 1. = 0 , \tag{12}$$

$$e^t = \left(2D \pm \sqrt{4D^2 - 4}\right)\Big/2 , \tag{13}$$

$$e^t = D + \sqrt{D^2 + 1} , \tag{14}$$

and

$$\cosh^{-1}(D) = t = \ell n \left(D + \sqrt{(D + 1)(D - 1)}\right) . \tag{15}$$

6. Sum quadratures of length Δt between spline knots

$$\int_0^{t_1} + \int_{t_1}^{t_2} + \int_{t_2}^{t_3} + \cdots \int_{t_{n-2}}^{t_{n-1}} \tag{16}$$

where

$$\Delta t = \min\left(\cosh^{-1}\frac{1}{\mu c}\ ,\quad 1.\right) \tag{17}$$

and terminate on an

$$\text{estimated truncation error} = \frac{\pi \text{ OF} \left(\frac{w_{st}}{2} + w_s \cdot \bar{\theta}\right) e^{-\mu c \cosh \bar{t}}}{c} \quad . \tag{18}$$

by means of

$$\left|\frac{\text{estimated truncation error}}{\text{total quadrature sum}}\right| \le \text{TOL}, \quad \text{TOL} = 1.\text{E} - 4 \quad , \tag{19}$$

where

$\bar{t}$ is the endpoint of integrations and $\bar{\theta}$ corresponds to $\bar{t}$.

7. If the integration does not terminate in step 6 then for $\int_{t_{n-1}}^{\infty}$, sum

the integrals

$$\int_{t_{n-1}}^{\Delta t_1} + \int_{\Delta t_1}^{\Delta t_2} + \cdots \int_{\Delta t_{m-1}}^{\Delta t_m} \quad . \tag{20}$$

where

$$\Delta t_i = \min\left(\frac{1}{\mu c \sinh t}\ ,\quad 1.\right) \quad , i = 1,\ 2,\ \cdots \tag{21}$$

$$\text{until} \left|\frac{\text{estimated error}}{\text{total quadrature sum}}\right| < \text{ETOL}, \quad \text{ETOL} = 5.\text{E} - 6 \quad . \tag{22}$$

The truncation error for steps 6 and 7 is estimated by means of

$$R = \frac{1}{c} \int_{\bar{t}}^{\infty} \frac{e^{-\mu c \cosh t}\ OF\left(\frac{w_s t}{2} + w_s,\ \theta\right)\ dt}{\cosh t} \tag{23}$$

$$\le \frac{OF\left(\frac{w_s t}{2} + w_s,\ \bar{\theta}\right)}{c} \int_{\bar{t}}^{\infty} \frac{e^{-\mu c \cosh t}}{\cosh t}\ dt \tag{24}$$

since OF is monotone decreasing in t (s increases with t, r increases with s, and θ increases with r). Then

$$R \le \frac{OF\left(\frac{w_s t}{2} + w_s,\ \bar{\theta}\right)}{c}\ e^{-\mu c \cosh \bar{t}} \int_{\bar{t}}^{\infty} \frac{dt}{\cosh t} \tag{25}$$

so,

$$R \le \frac{OF\left(\frac{w_s t}{2} + w_s,\ \bar{\theta}\right)}{c}\ e^{-\mu c \cosh \bar{t}} \left(2 \int_{0}^{\infty} \frac{e^{t}\ dt}{e^{2t} + 1}\right) \tag{26}$$

and

$$R \le \frac{OF\left(\frac{w_s t}{2} + w_s,\ \bar{\theta}\right)}{c}\ e^{-\mu c \cosh \bar{t}} \left(2 \tan^{-1} e^{t} \Big|_{0}^{\infty}\right) \tag{27}$$

and

$$R \le \pi\ \frac{OF\left(\frac{w_s t}{2} + w_s,\ \bar{\theta}\right)}{c}\ e^{-\mu c \cosh \bar{t}}\ . \tag{28}$$

II. Consider

$$\int_a^b dy \int_a^\infty \frac{e^{-\mu\sqrt{x^2+y^2}}\left(c\sqrt{x^2+y^2}+1.\right)}{\left(\sqrt{x^2+y^2}\right)^2}\,dx \quad , \tag{29}$$

where

$$a = \frac{w_{st}}{2} \qquad \text{and} \qquad b = \frac{w_{st}}{2} + w_s \quad .$$

Converting to polar form, Expression 29 can be rewritten as

$$\int_{\theta_1}^{\theta_2}\left[\int_{r_1(\theta)}^{r_2(\theta)} \frac{e^{-\mu r}(cr+1)\,r\,dr}{r^2}\right] d\theta \quad , \tag{30}$$

where

$$\theta_1 = 0, \quad \theta_2 = \frac{\pi}{4}, \quad r_1(\theta) = \frac{a}{\sin\theta}, \quad r_2(\theta) = \frac{b}{\sin\theta}$$

and

$$F(r_1, r_2) = \int_{r_1(\theta)}^{r_2(\theta)} \frac{e^{-\mu r}(cr+1)\,r\,dr}{r^2} \quad .$$

Thus,

$$\int_{\theta_1}^{\theta_2}\left[\int_{r_1(\theta)}^{r_2(\theta)} \frac{e^{-\mu r}(cr+1)\,r\,dr}{r^2}\right] = \int_{\theta_1}^{\theta_2} F(r_1, r_2)\,d\theta \tag{30a}$$

$$F(\alpha, \beta) = \int_\alpha^\beta e^{-\mu r}\left(c + \frac{1}{r}\right) dr \tag{31}$$

so

$$F(\alpha, \beta) = c\int_\alpha^\beta e^{-\mu r}\,dr + \int_\alpha^\beta \frac{e^{-\mu r}}{r}\,dr \tag{32}$$

Evaluating 32,

$$F(\alpha, \beta) = \frac{c}{\mu} \left[-e^{-\mu\beta} + e^{-\mu\alpha}\right] + \left[\frac{1}{\alpha^0} E_1(\mu\alpha) - \frac{1}{\beta^0} E_1(\mu\beta)\right] \tag{33}$$

or

$$F(\alpha, \beta) = \frac{c}{\mu} \left[e^{-\mu\alpha} - e^{-\mu\beta}\right] + \left[E_1(\mu\alpha) - E_1(\mu\beta)\right] \quad . \tag{34}$$

The exponential integral was evaluated using the routine MMDEI from IMSL (International Mathematics and Statistical Libraries, Inc.).[2]

III. Consider

$$I(d, \mu) = \int_d^{\infty} \frac{e^{-\mu r}\left(c_2 r + c_1\right)}{r\left(r^2 - d^2\right)^{1/2}} \, dr \quad . \tag{35}$$

Let

$$I_1 = c_2 \int_d^{\infty} \frac{e^{-\mu r}}{\left(r^2 - d^2\right)^{1/2}} \, dr = c_2 K_0(\mu d) \quad . \tag{36}$$

where $K_0(x)$ is the modified Bessel function of the second kind anc

$$I_2 = c_1 \int_d^{\infty} \frac{1}{r} \frac{e^{-\mu r} \, dr}{\left(r^2 - d^2\right)^{1/2}} = \int_d^{\infty} \frac{\int_{\mu}^{\infty} e^{-tr} \, dt}{\left(r^2 - d^2\right)^{1/2}} \, dr \quad . \tag{37}$$

This can be rewritten as

$$I_2 = \int_{\mu}^{\infty} \left(\int_d^{\infty} \frac{e^{-tr} \, dr}{\left(r^2 - d^2\right)^{1/2}} \right) dt = \int_{\mu}^{\infty} K_0(td) \, dt \tag{38}$$

or

$$I_2 = \frac{1}{d} \int_{\mu d}^{\infty} K_0(w) \, dw \quad , \quad td = w \quad . \tag{39}$$

Then,

$$I(d, \mu) = c_2 K_0 (\mu d) + \frac{c_1}{d} \int_{\mu d}^{\infty} K_0 (w)\, dw \quad . \tag{40}$$

The routines BESK01[3] and INTK0[4] were used to evaluate the K_0 Bessel function and its integral respectively.

IV. Consider

$$\int_a^{\beta} \int_d^{\infty} \frac{e^{-\mu r}\left(c_2 r + c_1\right)}{r\left(r^2 - d^2\right)^{1/2}}\, dr\, d(d) \quad . \tag{41}$$

Applying the conclusions of Section III above,

$$\left.\begin{aligned}
&\int_a^b \left[c_2 K_0 (\mu d) + \frac{c_1}{d} \int_{\mu d}^{\infty} K_0 (w)\, dw \right] d\,(d) \\
&= \frac{c_2}{\mu} \int_{\mu a}^{\mu b} K_0 (t)\, dt + \int_a^b \frac{c_1}{d} \int_{\mu d}^{\infty} K_0 (w)\, dw \;\; d(d) \\
&= \frac{c_2}{\mu} \int_{\mu a}^{\mu b} K_0 (t)\, dt + \int_{\mu a}^{\mu b} \left(\frac{c_1}{t} \int_t^{\infty} K_0 (w)\, dw \right) dt \quad .
\end{aligned}\right\} \tag{42}$$

To retain significance, we compute

$$\int_{x_1}^{x_2} K_0 (t)\, dt = \int_0^{x_2} - \int_0^{x_1} \quad \text{if } x_2 < 1 \tag{43}$$

and

$$\int_{x_1}^{x_2} K_o(t)dt = \int_{x_1}^{\infty} - \int_{x_2}^{\infty} \quad \text{if } x_2 > 1 \tag{44}$$

where the forms on [0, x] and [x, ∞] are available from INTK0.[4]

The outer double integral form can be evaluated using GAUS8[5] with INTK0 on [x, ∞].

V. Consider

$$\int_a^{\infty}\left(\int_x^{\infty} \frac{e^{-\mu r}\left(c_2 r + 1\right)}{r\left(r^2 - x^2\right)^{1/2}} dr\right) dx \tag{45}$$

From Section IV if $b \to \infty$, then Expression 45 can be rewritten as

$$\frac{c_2}{\mu} \int_{\mu a}^{\infty} K_0(t)\,dt + \int_{\mu a}^{\infty}\left(\frac{c_1}{t}\int_t^{\infty} K_0(w)\,dw\right) dt \quad . \tag{46}$$

This integral can then be evaluated using GAUS8[1] and INTK0,[4] taking $\Delta t = 1$ and $t_0 > 5$ and terminating integration when the estimated error divided by the accumulated sum becomes less than a specified tolerance:

$$\frac{\displaystyle\int_{t_0}^{\infty} \frac{1\ e^{-t}}{\sqrt{\pi/(2t)}}}{\text{Accumulated Sum}} \le \frac{\dfrac{e^{-t0}}{\sqrt{\pi/(2t_0)}}}{\text{Accumulated Sum}} < \text{TOL} \ . \tag{47}$$

VI. Consider

$$\int_a^b \frac{e^{-\mu r}\left(c_2 r + c_1\right)}{r}\, dr \quad . \qquad (48)$$

Expression 48 can be shown to be equal to

$$c_2 \int_a^b e^{-\mu r}\, dr + c_1 \int_a^b \frac{e^{-\mu r}}{r}\, dr \qquad (49)$$

which, when evaluated, equals

$$\frac{c_2}{\mu}\left(e^{-\mu a} - e^{-\mu b}\right) + c_1 \left[E_1\left(\mu a\right) - E_1\left(\mu b\right)\right] \quad . \qquad (50)$$

The exponential integral was evaluated using the routine MMDEI.[2]

VII. Consider

$$\int_c^{\infty} \frac{e^{-\mu r}}{r^2}\, OF_i\,(\theta)\, dr \qquad (51)$$

where

$$c = \sqrt{\left[\sqrt{2}\left(w_{st} + w_s\right)\right]^2 + \left[h\left(i - .5\right)\right]^2} \qquad \text{and}$$

$$\theta = \tan^{-1} \frac{\sqrt{\left[.5\left(D' + w_{st}\right)\right]^2 + \left[h\left(i - .5\right)\right]^2}}{\sqrt{2}\left(\frac{w_{st}}{2} + w_s\right)} \quad .$$

Since $OF_i(\theta)$ is constant for each i, the function $OF_i(\theta)$ can be removed from the integral:

$$OF_i(\theta) \int_c^{\infty} \frac{e^{-\mu r}}{r^2} \, dr \quad . \tag{52}$$

To evaluate this revised integral let $r = cx$, then

$$\int_1^{\infty} \frac{e^{-\mu cx}}{c^1 x^2} \, dx = \frac{1}{c} E_2 \left(\mu c\right) \quad . \tag{53}$$

Since

$$xE_1 + E_2 = e^{-x} \quad , \tag{54}$$

$$E_2 = e^{-x} - xE_1 \quad . \tag{55}$$

This expression can be evaluated using the exponential routine EXP, and the exponential integral routine MMDEI.[2]

TABLE I

List of Variables

Symbol	Description	Units	Equations in Which Variable Appears
DR	dose-rate	mrem/hr	1,2,3
K, K_o	exposure-source dose-rate shape factor	$\frac{mrem\text{-}m^2}{hr}$	1,2,5,6,7,9,10,11, 12,14,15,23,24,25, 26,27,29,31,32,33, 34,35,36,37,38,39, 41,42,43,46
μ, μ_{air}, μ_b	linear attenuation coefficient (general, air, buildings)	m^{-1}	1,2,5,6,7a,10,11,12, 13,14,15,17,23,24,25, 26,31,32,33,36,37,38, 39,41a,42,43,46
r	distance from source to point of exposure	m	1,2,5,6,7a,10,11,12,13, 14,15,18,20,23,31,32, 36,37,38,39,41a,42,43, 46
TI	transport index	*	2,9,23,32,33,34,35, 36,37,38,39,41,42,43, 44,46
PPS	packages per shipment	*	2,9,23,32,33,34,35,36, 37,38,39,41,42,43,44
D, D(x)	individual dose	rem	3,5,6,7,8,10
t	time	hr	3,4
x	distance	m	4,5,7,7a,8,9,10,11, 12,13,14,15,34,41,41a
v	velocity (general)	m/sec	4,5,6,7,10,11,12
d	minimum perpendicular distance from shipment path	m	6,8,11,12,13,14,15
PD, PD_{depot}, PD_{Rw}, PD_{term}, PD_{dock}, PD_{Stor}	population density (general, rail, depot, rail right-of-way, air terminal, dock area, warehouse)	$persons/km^2$	8,21,38,40,41,42,43, 46
ID, ID , ID , ID_{CD}, $ID_{stopped}$, ID_S, ID_{oD}, ID_{crew} ID_H, ID_{Stor}	integrated population exposure	person-rem	8,9,11,12,13,14,15, 16,23,24,25,26,27, 29,31,32,33,34,35,36, 37,38,39,41,42,43,44, 45,46

Table I (cont.)

Symbol	Description	Units	Equations in Which Variables Appear
L	distance traveled in cell	m	8,9,9a,12,13,16,23, 27,29,31,32,33,34,35, 36,37,39,41
max	maximum distance of interest in strip integration	m	8
PedD	number of pedestrians in grid square at a given time	persons/km^2	9,11,12,14,15,34,40
w_{Fc}	street width	m	9,14,15,16,19,20,23, 24,25,31,32,34
w_s	sidewalk width	m	9,11,12,13,14,15,19, 20,23,34
A	area of grid square	m^2,km^2	9,21,23,34,37,41
f_{st}	fraction of area occupied by streets	*	9,23,34,37
ABD	albedo dose factor	*	9,34
$\overline{V}$,V_f	average shipment velocity (street, freeway)	m/sec	9,9a,16,23,28,33,34, 36,37,40
v_p	pedestrian velocity	m/sec	9,14,15,16,34
V_c	cruising velocity	m/sec	9a,24,25,29,30,31,32, 35
ξ	fraction of intersections at which shipment stops	*	9a,26,27,29,32,35
Ω	delay time at intersections	hr	9a,27,29,32,35
D'	average block length	m	9a,24,25,27,28,29,32, 35
A_1,A_2 α_1,α_2	buildup factor equation constants	*	17
E	incident photon energy	MeV	17
θ	plane angle between raypath and building face	*	19

Table I (cont.)

Symbol	Description	Units	Equations in Which Variables Appear
w_b	building thickness	m	17,23,37
h	height per floor	m	19,20,23,37
n	number of floors in building	*	19,20,22,23,37
r'	perpendicular distance from source to center of street in front of buildings	m	19,20
PPB	people in buildings	persons	21,22
TC	transient clientele	persons/km^2	21,40
PPF	persons per floor	persons	22,23,37
i	summation variable over building floors	*	23,37
d_1, d_1^f	vehicle separation distance during cruise phase (street, freeway)	m	24,25,29,32,35
ℓ	average vehicle length	m	24,25,26,27,29,32,35, 36
j	summation variable over discrete vehicles	*	25,26
f, f_f	vehicle bunching factor (streets, freeways)	*	27,29,32,35,36
δ	vehicle separation distance while stopped	m	26,27,32,35
LPD	linear population density	persons/m	30
N, N_f, N_T	one-way hourly traffic count (street, freeway, rail)	veh/hr	30,31,32,36,39,40
PPV,PPT	people per vehicle (auto/truck/bus,train)	persons/veh	30,31,32,35,36,39,40
N_C	number of crewmen	*	33
d_2	source-to-crew distance	m	33
w_f	freeway width (centerline-to-centerline)	m	36,37

Table I (cont.)

Symbol	Description	Units	Equations in Which Variable Appears
$\beta_1, \beta_2, \beta_3$	minimum separation distances	m	23,37
V_T	train velocity	m/sec	39,41
$\Delta T_{depot}, \Delta T_{term}, \Delta T_{dock}, \Delta T_{Stor}$	average stop time (rail stations, air terminals, dock areas, warehouses	hr	38,42,43,46
r_1, r_4, r_6, r_8	minimum exposure radii	m	38,42,43,46
r_2, r_5, r_7, r_9	maximum exposure radii	m	38,42,43,46
r_3	distance between passing trains	m	39
R_W	rail right-of-way distance	m	41
N_H	number of handlings	*	44
K_1	dose rate at 3 feet from a cask	mrem/hr	45
K_2	length of time spent by handler in dose field	hr	45
K_3	number of handlers required	*	45
K_4	number of transfers per shipment	*	45

Table II

List of Constants

Symbol	Value	Units	Equations
Q_1	2.78×10^{-13}	$\frac{\text{rem-hr-km}^2}{\text{mrem-sec-m}^2}$	9,23,34,37,41
Q_2	3600	$\frac{\text{sec}}{\text{hr}}$	9a,28,29,30,32,40
Q_3	7.72×10^{-11}	$\frac{\text{rem}}{\text{mrem}} \times \frac{\text{hr}^2}{\text{sec}^2}$	31,39
Q_4	$2.78 * 10^{-7}$	$\frac{\text{rem-hr}}{\text{mrem-sec}}$	32,33,35,36
Q_5	1×10^{-9}	$\frac{\text{rem-km}^2}{\text{mrem-m}^2}$	38,42,43,46
Q_6	2.5×10^{-4}	$\frac{\text{person-rem}}{\text{handling/TI}}$	44
Q_7	1800	$(0.5)\ \frac{\text{sec}}{\text{hr}}$	29,32,35

Table III

List of Functions

Symbol	Description	Equations
$B(r), BF(E, w_s), B_{air}(r), BF, B_b$	dose buildup factor	1,2,5,6,7a,10,11 12,13,14,15,17,18, 31,32,33,36,37,38, 39,41a,42,43,46
$OF(r)$, $OF_i(r)$	obliqueness factor	23,37

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2. International and Statistical Libraries, Inc., The IMSL Library, IMSL LIB03-0006, IMSL Library 3, Edition 6, (Fortran)CDC 6000/7000, CYBER 70/170 Series, July 1977,

3. Amos, D.E. and S.L. Daniel, CDC 6600 Subroutines for Bessel Functions $I_\nu(x)$, $\nu = 0$, $-\infty < x < \infty$ and $K_\nu(x)$, $\nu = 0, 1$, $x > 0$, Sandia Laboratories SAND75-0149, September 1975.

4. Amos, D.E. and S.L. Daniel, CDC 6600 Subroutines for Integrals of (sin t)/t, (cos t)/t, $K_0(t)$, Sandia Laboratories Report SAND76-0062, February 1976.

APPENDIX E

Analysis of the Radiological Consequences of Accidents Involving Radioactive Materials

1. Introduction

Accidents involving radioactive materials may compromise the packaging integrity. If the packaging integrity is compromised, the contained material may be dispersed in such a way that the surrounding population is exposed to an inhalation hazard, or the material may become unshielded and the surrounding population is exposed to penetrating radiation emitted by the material. If the packaging remains intact, the radiological consequence results from the delay associated with the accident. A vehicle transporting radioactive material may be involved in a "fender-bender" on a busy downtown street. During the time required for law enforcement and/or other emergency equipment to arrive, analyze the situation, and remove the vehicles, the surrounding population receives an additional radiation dose from the still-intact package inside the damaged transport vehicle.

Accidents in which package integrity is compromised are further divided into two categories: those involving shipments of dispersible materials, and those involving shipments of non-dispersible (special-form) materials. In the first case, the atmospheric dispersion of released material and the consequent radiological effect are evaluated. In the second case, any exposed radioactive material is treated as a point source of external penetrating radiation. In each of these cases, radiological effects resulting from material which remains in the broken package, and the material which spills out but does not become airborne are also evaluated.

2. Material Characterization from an Accident Viewpoint

The consequences of an accident involving release of or exposure to radioactive material depend upon certain material-dependent dosimetric parameters. These include the rem-per-curie-inhaled value, the photon energy, the particular organ or organs effected, the fraction of released material which becomes aerosolized, the respirable fraction, and the resuspension dose factor. The method of obtaining values for each of these factors is discussed in Appendix A, and the method in which they are used is discussed in this appendix and in Appendix H.

3. Accident Environment/Package Release Model

The model which is used to describe the severity of accident environments and to relate package response to those environments is essentially the same as that used in Reference 1 and so will be merely summarized in this appendix. Detailed data for occurrence probabilities by mode are contained in Appendix A.

3.1 Accident Environment Severity Classification

The fraction of contained radioactive material which is released to the environment in an accident depends upon the severity of the accident, and upon the accident resistance of the packaging. Very severe accidents might be expected to release a a large fraction of the contained radioactive material carried, while minor accidents are unlikely to cause any release. Thus, in addition to the overall accident rate for each mode, the distributions of accidents according to severity must be determined.

The eight-severity classification scheme developed in Reference 1 assigns a principal accident deformation force (impact, crush, puncture, or fire duration) to each transport mode, and assigns each of the eight severity categories a mode-dependent occurrence probability. Combined environments have been examined in other studies;[2] and, as a result of those studies, the only combinations allowed in this model are combinations involving a single deformation force and fire.

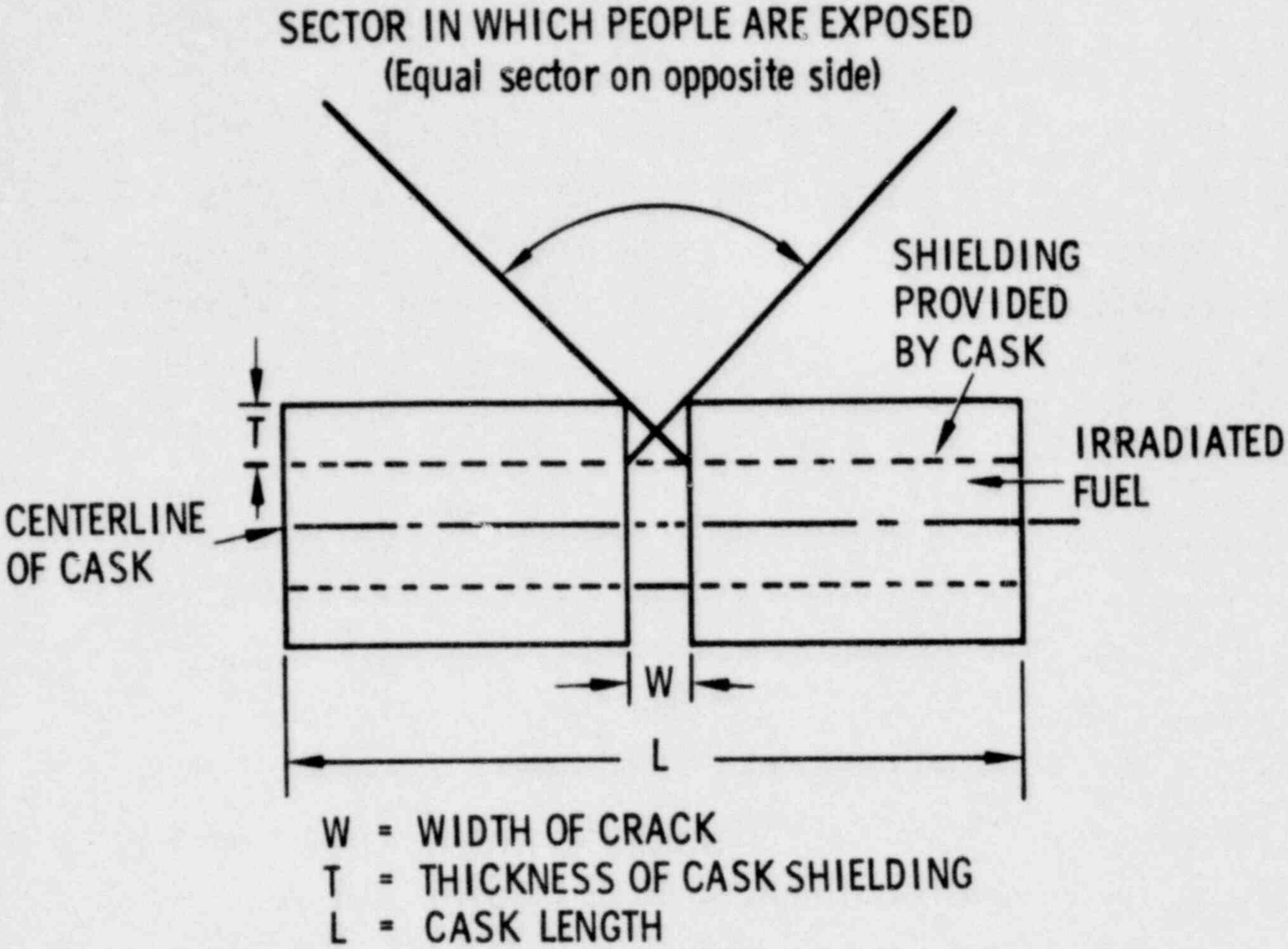
Once the occurrence probabilities for environments of each severity have been determined, they are applied to the overall accident rate for a specific mode to get an accident rate for severity and mode. The values used for overall accident rate and severity occurrence probabilities are given in Appendix A.

3.2 Package Response Model

In order to assess the risk of a transportation accident, one must be able to predict the response of a particular package type to an accident of given severity. In particular, one needs to know the fraction of the total package contents which would be released. The actual releases for a given package type would not necessarily be the same for a number of accidents of the same severity class. In some cases there may be no release, while in others there may be a release of some fraction of the package contents. Indeed, in a given accident involving a number of radioactive material packages transported together, some of the packages may release part of their contents while others have no release at all. The approach taken in Reference 1 and this assessment is to derive a single value which represents the average release fraction for each severity category and package type (independent of mode) and assume <u>all</u> such packages, including separate packages in a multi-package shipment, respond to such an accident in the same way.

There are two basic package classifications which must be explained further: packages containing dispersible material and packages containing special-form materials (non-dispersible under accident conditions). In the former case, the concept of "release" is straightforward: released material is that which ends up beyond the outer boundary of the packaging after an accident. In the case of special-form materials, it is not quite so straightforward. As discussed earlier, the radiological consequence of an accident involving a special-form shipment would probably be a loss of shielding. For small packages, this is taken to be identical to the release fraction for a dispersible material carried in that same package. For a large package such as a spent fuel cask, however, the effect of loss of shielding is modeled by assuming that a circumferential crack is produced in the container by the accident forces. The "release fraction" for the loss of shielding case is not really a release fraction at all, but is the product of the fraction of the source exposing the surrounding population and the fraction of the surrounding area within the sector being exposed as shown in Figure 1. The computation of the integrated population dose is then carried out assuming an effective point source whose strength is the total contained curies multiplied by the release fraction integrated over the various populations at risk.

The values used for release fractions for the various package types are given in Table 1.



FRACTION OF SURROUNDING POPULATION EXPOSED $= 1 - \frac{2}{\pi} \tan^{-1} \left(\frac{T}{W}\right)$

Figure 1. Release Fraction

TABLE 1

RELEASE FRACTIONS FOR PACKAGE TYPES

Severity Category	LSA Drum	Type A	Type B No Pu	Type B 1975 Pu	Cask (exposure)	Cask (release)
I	0	0	0	0	0	0
II	.01	.01	0	0	0	0
III	.1	.1	.01	0	0	.01
IV	1.0	1.0	.1	0	0	.1
V	1.0	1.0	1.0	0	0	1.0
VI	1.0	1.0	1.0	.01	3.18×10^{-7}	1.0
VII	1.0	1.0	1.0	.05	3.18×10^{-5}	1.0
VIII	1.0	1.0	1.0	.1	3.12×10^{-3}	1.0

4. Dose Computation

In this section, the mathematical basis for dose computation will be provided and the actual expressions used to calculate doses will be derived.

Figure 2 shows the various doses of concern resulting from accidents involving various types of materials. Doses resulting from special-form materials will be discussed first.

4.1 Accident Doses From Special-Form Sources

If a shipment of special-form material is involved in an accident which is sufficiently severe to compromise the integrity of the container, the amount of shielding around the source will be effectively reduced, resulting in exposure to surrounding people. The basic expression for dose rate under these circumstances is derived based on information in Reference 3:

$$DR = \frac{Q_1 * n_2 * RF * PPS * E_d * \mu * e^{-\mu r} * B(r)}{r^2} \tag{1}$$

where Q_1 = units conversion factor

n_2 = number of curies per package

RF = release fraction

PPS = number of packages per shipment

μ = attenuation coefficient (m^{-1})

E_d = the gamma energy released per disintegration (MeV)

r = distance from source (m)

B(r) = dose buildup factor.

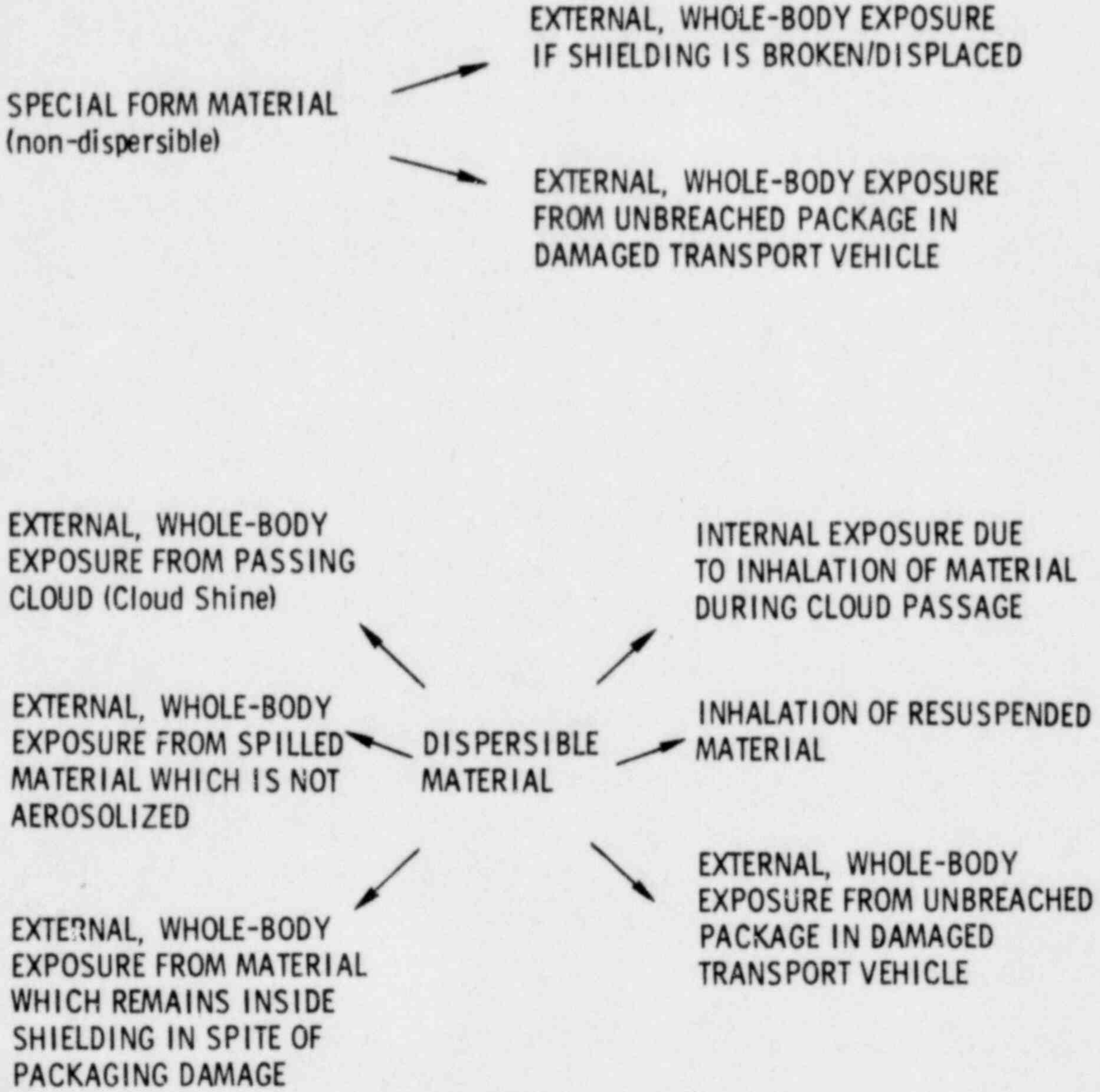


Figure 2. Dispersibility Characteristics

This expression is analogous to that used earlier to derive expressions for accident-free dose (Appendix D) and can be similarly manipulated.*

4.1.1 Dose to pedestrians

The individual dose received by a pedestrian at a distance r from an accident involving an exposure source is given by

$$\phi = \frac{K * e^{-\mu r} * B(r) * \Delta T_a}{r^2} , \tag{2}$$

where T_a = accident delay time (hr)

K = source term. (See following discussion.)

In addition to the unshielded material, that material which remains shielded will continue to expose people while initial emergency action is being taken to shield the exposed material. In this case the source term is simply $K_0 * TI * PPS * (1 - RF)$. Thus, the general source term for an accident involving a special form shipment can be written as:

$$K = (Q_1 * n_2 * PPS * \mu * E_d * RF) + (K_0 * TI * PPS * (1 - RF)), \tag{3}$$

where K_0 = shape factor for specific package type (m^2)

TI = transport index for package (equivalent to mrem/h^R).

*A complete list of variables, constants, and functions used in this development is given in the addendum to this appendix.

In order to compute dose from accidents involving special-form sources, the concept of a severity-dependent delay time (ΔT_a) is introduced to specify the length of time the shipment remains at the accident scene.

The integrated dose geometry is illustrated in Figure 3. An intersection accident geometry is chosen because not only do more accidents at greater severity occur at intersections, but also the potential number of exposed persons is larger in this geometry. Pedestrians are exposed on eight sidewalk segments, so the expression for integrated dose can be written as

$$ID = Q_2 * 8 * PedD * K * \Delta T_a *$$

$$\int_{w_{st}/2}^{\left(w_{st}/2 + w_s\right)} dx \int_{w_{st}/2}^{\infty} \frac{e^{-\mu_{air}\sqrt{x^2+y^2}} \; B_{air}\left(\sqrt{x^2 + y^2}\right) dy}{\left(\sqrt{x^2 + y^2}\right)^2} \quad , \tag{4}$$

where Q_2 = units conversion factor

K = source term (see Equation 3)

$PedD$ = pedestrian density (persons/km^2)

w_{st} = street width (m)

w_s = sidewalk width (m).

Using this approach, there is some overlap in the corners of the sidewalks as is shown on Figure 3. However, this overlap is removed by changing to polar coordinates and modifying the limits of integration.

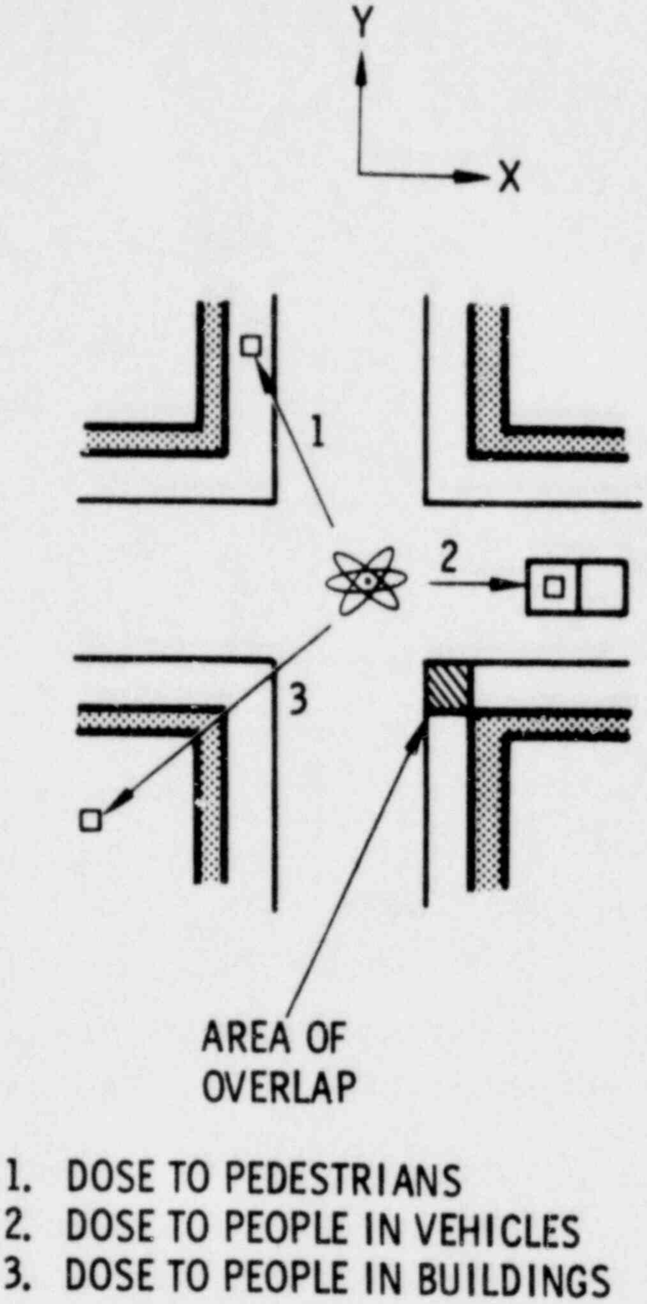


Figure 3. Dose Due to Special Form Sources

4.1.2 Dose to People in Buildings

The individual dose to a person in a building will depend upon the floor that person is on and his distance "down the block" from the shipment. With those constraints on r, the individual dose expression can be written:

$$\phi = K * \Delta T_{\alpha} * e^{-\mu_b w_b} * B_b(w_b) * OF(r) * \frac{e^{-\mu_{air} r}}{r^2} , \qquad (5)$$

where $OF(r)$ = obliqueness factor (see Appendix D)

w_b = building wall thickness (m)

μ_b = linear attenuation coefficient for building material (m^{-1})

The buildup factor assumptions discussed in Appendix D are also made in this case.

In order to compute integrated dose to people in buildings, it is initially assumed that the people on the floor of a building are distributed adjacent to the inside of the outer wall. Since buildings are presumed to have four walls, the number of people per wall per floor in the entire cell is given by:

$$PPW = \frac{PPF}{4}, \qquad (6)$$

where PPF = number of people per floor.

Since accident rates are per unit distance traveled, a value for people per unit length of expos building (i.e., building perimeter) per route is needed:

$$PPL = \frac{PPW}{\sqrt{A * f_b}} * \frac{L * w_{st}}{A * f_{st}} , \tag{7}$$

where A = cell area (m^2)

f_b = fraction of cell area occupied by buildings

f_{st} = fraction of cell area occupied by streets

L = distance traveled in cell (m)

$\frac{L*w_{st}}{A*f_{st}}$ = fraction of all buildings in cell which are along route.

This assumes that building cross-sections are square, and gives a value of people per-unit-building perimeter distance along the route. Since only half of each building is exposed from a source centered in an intersection, and since buildings are assumed to be on each of the four corners of an intersection, the number of people exposed per floor per intersection is given by

$$\frac{PPF}{2} * \frac{1}{\sqrt{A * f_b}} * \frac{L * w_{st}}{A * f_{st}} \tag{8}$$

The number of people per floor is given by equation 22 of Appendix D. Based on these assumptions, the integrated dose measured at the vertical midpoint of the floor can be specified as:

$$\frac{PPF}{2} * \sqrt{A * f_b}$$

(9)

$$\frac{PPF}{2} * \frac{1}{\sqrt{A * f_b}} * \frac{L * w_{st}}{A * f_{st}}$$

where Q_3 = units conversion constant

OF = obliqueness factor (see Appendix D)

n = number of floors

h = height per floor (m)

$\beta_1 = \sqrt{[\sqrt{2}(w_{st/2} + w_, + w_b)]^2 + [h(i - .5)]^2}$.

4.1.3 Dose to P[illegible] in Vehicles

No shielding credit is taken for vehicles, so the individual dose to people in vehicles is identical to that developed in Equation 2 where $r > d_1$, (d_1 = minimum vehicle separation distance).

The integrated dose received by people in vehicles can be visualized by thinking of cars stopped at discrete distances from the source, as shown on Figure 4. The general approach used to compute dose to people in vehicles from normal transport can then be applied. Note that the example used is a two-lane bidirectional street intersection. This analysis would al[illegible] apply to either multi-lane or one-way streets.

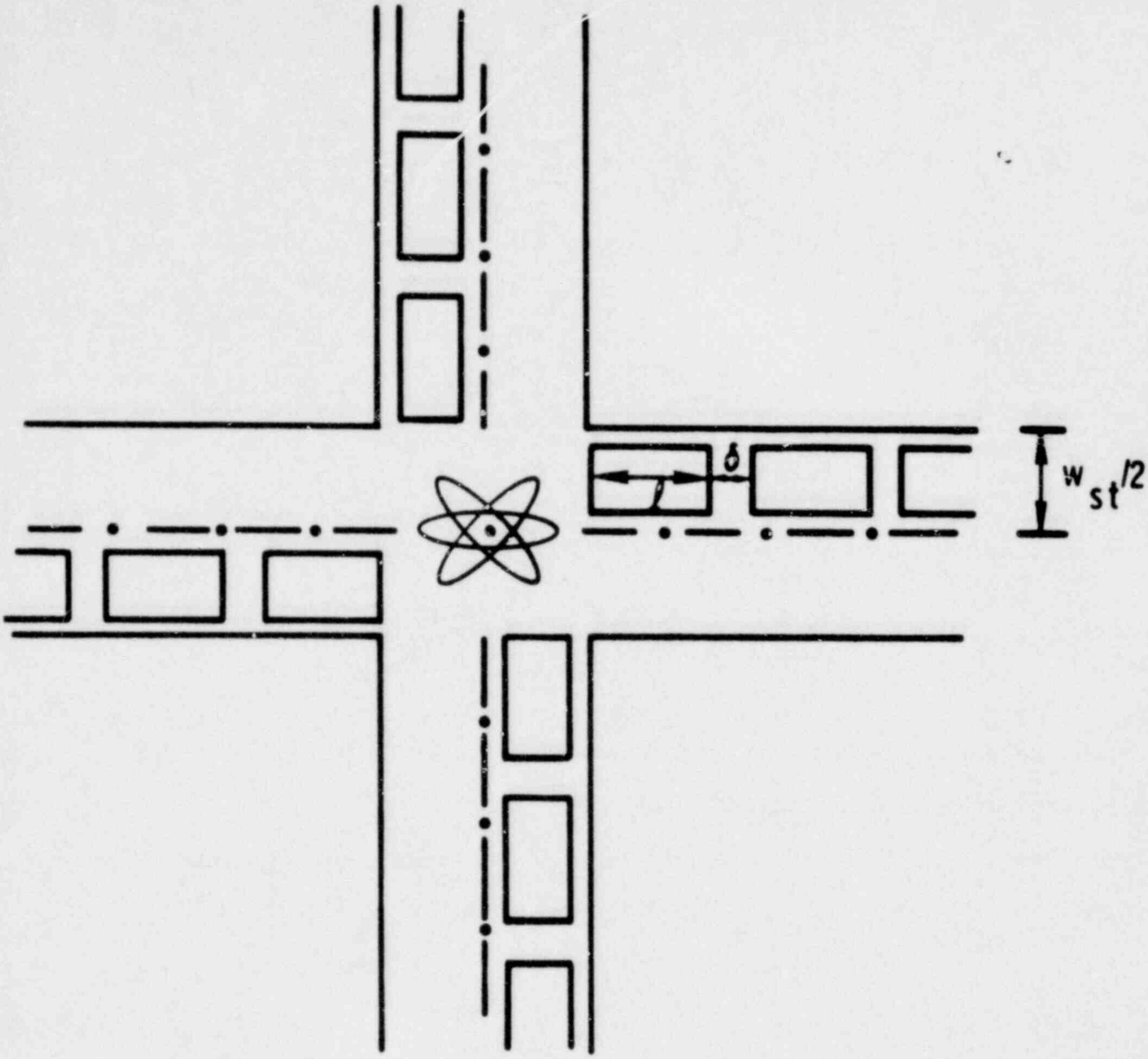


Figure 4. Exposure Geometry for Direct Exposure to People in Vehicles Resulting from an Intersection Accident

$$ID = Q_3 * PPV * 2 * K * L' * \Delta T_a * 2 * \sum_{j=1}^{\infty} \frac{e^{-\mu\left[W_{st}/2+(\delta+\ell)_j\right]}}{\left[W_{st}/2+(\delta+\ell)_j\right]^2} \quad . \qquad (10)$$

where j = summation index over vehicles

L' = number of lanes per side of the street

δ = average separation distance of stopped vehicles (m)

ℓ = average vehicle length (m)

PPV = number of people per vehicle.

Using assumptions discussed in Appendix D, this can be rewritten as

$$ID \le 4 * Q_3 * PPV * K * L' * \Delta T_a * \sum_{j=1}^{\infty} \frac{1}{\left(j + \frac{W_{st}}{2(\delta+\ell)}\right)^2} \quad . \qquad (11)$$

with the acknowledgment of approximately 7 percent overestimate of dose. This is equivalent to:

$$ID = Q_3 * PPV * 4 * K * L' * \Delta T_a * \frac{1}{(\delta+\ell)^2} * \left[1.64 - \sum_{j=1}^{E'} \frac{1}{j^2}\right] \quad . \qquad (12)$$

where $E' = \frac{W_{st}}{2(\delta+\ell)}$, rounded to the nearest integer value.

As discussed earlier, the analysis leading to Equation 11 is considered for all street types. However, freeways present some unique aspects which are discussed in the next section.

4.1.4 Special Form Source Accidents on Freeways

Since a relatively large amount of truck travel in urban areas is expected to occur on freeways, the unique aspects of this roadway type with respect to direct radiation exposure need to be accounted for.

4.1.4.1 Dose to Pedestrians Resulting from Special Form Source Accidents on Freeways

If the special form source accident occurs on a freeway, pedestrian dose is set to 0.

4.1.4.2 Dose to People in Buildings Resulting from Special-Form Source Accidents on Freeways

The geometry for dose to people in buildings from a freeway accident can be thought of as similar to the geometry for an accident which occurs midblock on a very wide street. Thus, the development leading to Equation 8 must be modified so that the number of people per floor being exposed are those facing the freeway, or 1/4 of those on the floor. Equation 8, therefore, becomes

$$\frac{PPF}{4} * \frac{1}{\sqrt{A * f_b}} * \frac{L * w_{st}}{A * f_{st}} \quad , \tag{13}$$

This is used in a modified version of equation 9 to give

$$ID_{bldg} = \frac{Q_3}{\sqrt{A * f_b}} * \frac{PPF}{4} * \frac{L * w_f}{A * f_{st}} * \Delta T_a * e^{-\mu_b w_b} * B_b(w_b) * K *$$

$$\sum_{i=1}^{n} \left[\int_{\beta_2}^{\infty} \frac{e^{-\mu_{air} r} OF_i(r) dr}{r^2} \right] . \tag{14}$$

where w_f = centerline-to-centerline freeway width (m)

$_2 = (w_f)^2 + [h(i - 0.5)]^2$.

4.1.4.3 Dose to People in Vehicles Resulting from Special Form Source Accidents on Freeways

Accidents on freeways seldom disable traffic in both directions so the model considers that the side of the freeway involving the shipment is essentially stopped, and that other traffic continues to move normally, as shown on Figure 5. It is assumed that the area around the vehicle is congested and vehicle separation in the area immediately surrounding the damaged vehicle is essentially equal to the value for intersections, δ , used in Equation 12. Using this and the bunching factor discussed in Appendix D, an expression for dose to people traveling the same direction as the shipment can be derived:

$$ID = Q_4 * K * PPV * \frac{2 * \Delta T_a * f_f}{\left(\delta + \ell\right)^2} , \qquad (15)$$

where Q_4 = units conversion constant

f_f = freeway bunching factor

The dose to people traveling in the direction opposite the shipment was derived in Appendix D and is modified to account for the fact that the shipment is stopped instead of moving. The net result for total exposure to people in vehicles from special form accidents on freeways is

$$ID = Q_4 * K * PPV * \Delta T_a \left[\frac{2f_f}{(\delta + \ell)^2} + \frac{Q_5 * N_f}{V_f} \int_{w_{f/2}}^{\infty} \frac{e^{-\mu r} B(r)\, dr}{r\left[r^2 - w_{f/2}{}^2\right]^{1/2}}\right] . \qquad (16)$$

where Q_5 = units conversion constant.

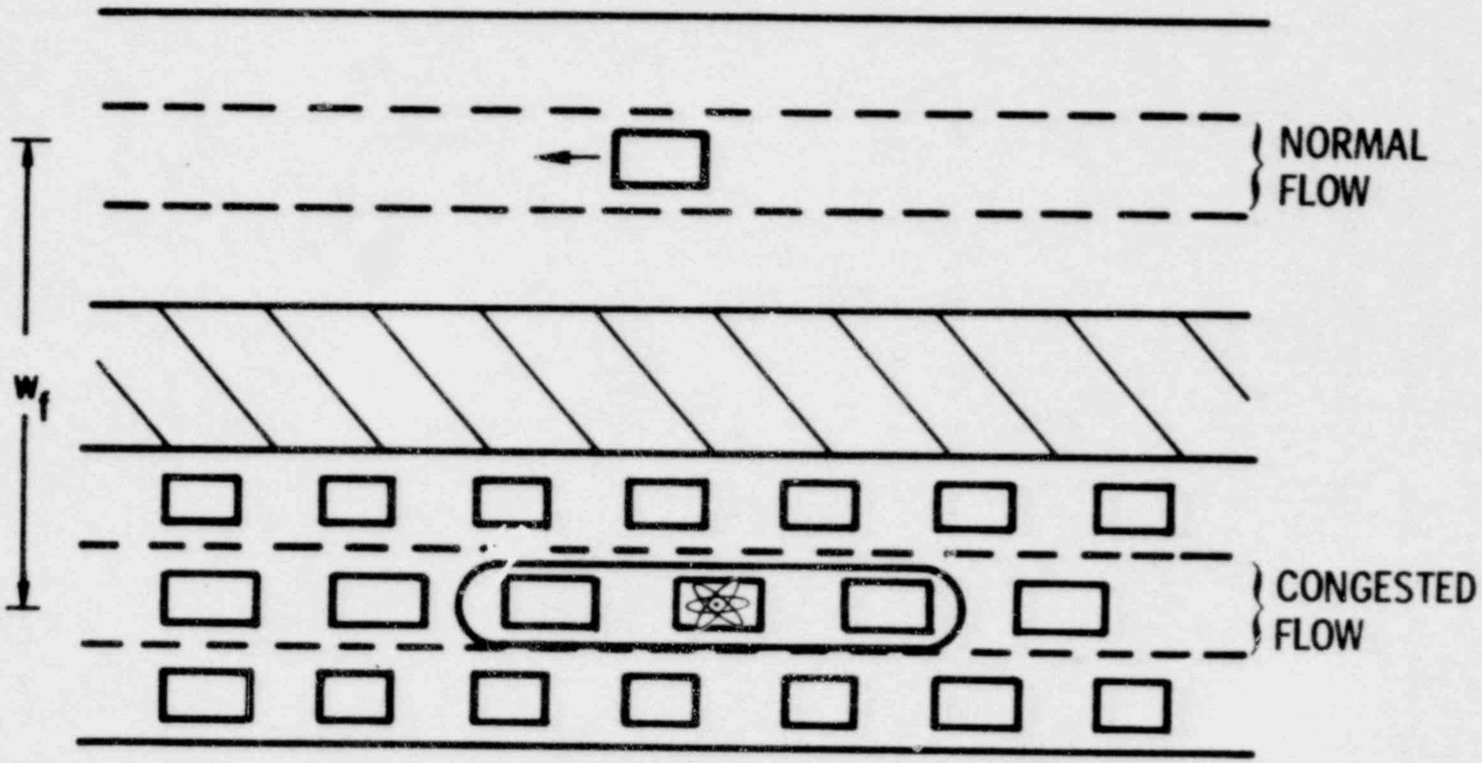


Figure 5. Special-form Dose to People in Vehicles for Freeway Accidents

5. Accidents Involving Dispersible Materials

As shown on Figure 1, an accident involving a dispersible material can result in up to five different doses. These will each be explored individually. The sixth dose, from the so-called nonrelease accident, is common to both special-form and dispersible materials and will be discussed in Section 6.

5.1 Doses Due to Inhalation of Radioactive Material During Cloud Passage and Resuspension of Deposited Material

5.1.1 Doses Due to Inhalation of Radioactive Material by Pedestrians

The individual critical-organ dose received by a pedestrian who inhales a given concentration of airborne radioactivity is given by

$$\phi_{inh} = n_2 * PPS * RF * AER * RESP * RPC * E * DF * BR * \Delta T, \quad (17)$$

where ϕ_{inh} = radiation dose from inhalation (rem)

n_2 = material per package (curies)

AER = fraction aerosolized

RESP = fraction res able

RPC = radiological toxicity to critical organ (rem-per-curie inhaled)

E = particle-size adjustment factor

DF = atmospheric dilution factor at street level ($Ci/m^3/Ci$ released)

BR = breathing rate (m^3/hr)

ΔT = total exposure time (hr).

The dilution factor, DF, varies as the cloud of debris is followed across the grid. The models used to predict this dispersion are discussed in Appendices F and G. If it is assumed that a pedestrian remains in one place for the duration of the cloud passage through the grid (for all practical purposes, this means within a specific cell in the grid), then the dose received by that pedestrian during a cloud transit consisting of t time steps, each of length ΔT, would be:

$$\phi = K' * \Delta T * \sum_{k=1}^{t} DF_k \tag{18}$$

where $K' = n_2 * PPS * RF * AER * RESP * RPC * E * BR$

DF_k = dilution factor in given cell for time step i

ΔT = length of time-step

t = total number of time-steps.

The integrated dose to pedestrians in a single cell during a single time-step from inhalation is computed by simply multiplying the dose received by each pedestrian by the number of pedestrians in the cell:

$$ID_{inh} = \phi_{inh} * PedD * \gamma * RDF, \tag{19}$$

where γ = fraction of area of cell covered by cloud during the specified time step

RDF = resuspension dose factor.

The resuspension factor is included in Equation 19 instead of Equation 18 because the impact of resuspension is significant only for long-term integrated doses. Since the small-scale atmospheric transport analysis requires a finer time scale, two time-step lengths are used: a small time-step, ΔT_S, for the small-scale analysis and a longer time-step, ΔT_I, for the large-scale analysis.

In order to combine doses absorbed during both the short and the long time-steps, integrated doses are summed over all time-steps in each cell, and over all cells which may be affected by the cloud. The pedestrian density is allowed to vary over these time-steps to simulate the diurnal variation throughout a city. The result is the integrated dose to pedestrians due to an accident of specific severity occurring in a specific cell along the route:

$$ID_{inh} = K' * \Delta T_S * RDF * \sum_{u=1}^{m} (DF_{1,u} * PedD_{1,u} * \gamma_u) + K' * \Delta T_L * RDF * \sum_{w=1}^{q} \sum_{z=1}^{p} (DF_{w,z} * PedD_{w,z} * \gamma_{w,z}), \qquad (20)$$

where m = number of short time steps (short-term atmospheric transport

q = number of long time steps (long-term atmospheric transport)

p = number of cells in grid

ΔT_S = length of small time-step (hr)

ΔT_L = length of long time-step (hr).

The integrated dose is split into the dose accumulated during the small-scale atmospheric transport analysis in the cell where the accident occurred, and dose accumulated during the large-scale atmospheric transport analysis in all cells (including the cell where the accident occurred). This approach was chosen as a result of distance constraints on the small-scale atmospheric transport analysis.

5.1.2 Doses Due to Inhalation of Radioactive Material by People in Vehicles

The dose received by people in vehicles as the cloud of debris from an accident passes is analogous to the dose received by pedestrians. The individual dose for one severity, one time-step, and one cell is again given by Equation 17. Since it is not possible to predict whether or not drivers will have windows up or down, or whether they will have vents open or closed, no credit is taken for possible filtration of cloud debris as it enters the vehicle. As was the case for pedestrians, the total individual dose for a given accident can be given by Equation 20, again using ground level dilution factors. The integrated dose computation requires the population density for people in vehicles in each cell in the grid. If this density is incorporated, the general expression for integrated dose to people in vehicles from an accident of specific severity occurring in a specific cell becomes

$$ID_{veh} = \left[N'_1 * PPV * \Delta T_s * K' * RDF * \sum_{u=1}^{m} \left(DF_{1,u} * \gamma_u\right)\right] \qquad (21)$$

$$\left[\Delta T_L * K' * RDF * \sum_{w=1}^{q_1} \sum_{z=1}^{p_1} \left(N'_{w,z} * DF_{w,z} * \gamma_{w,z}\right)\right] ,$$

where N' = total vehicles in cell at given time (veh/km^2).

5.1.3 Doses Due to Inhalation of Radioactive Material by People in Buildings

The time-dependent concentration of radioactive material inside a building, and, therefore, the radiation exposure to people in that building, depend on a number of factors. The rate at which contaminants enter the building depends on the air exchange, or infiltration, rates of outside air into the building. As particulate materials enter the building, either through a ventilation system or by diffusion processes through walls, etc., some fraction is filtered out. Radioactive decay, deposition on surfaces internal to the building, and recirculation through ventilating filters and ducts also act to reduce the internal concentration. Using a building air exchange model developed in Reference 4, an equation can be developed which relates the dose received by an individual inside a building to the dose received by an individual outside the building:

$$\frac{\phi_{inside}}{\phi_{outside}} = \frac{F}{1 + \frac{D_1 + \lambda + K'\epsilon_r}{R}}, \qquad (22)$$

where F = building filtration factor

D_1 = deposition factor (hr^{-1})

λ = radioactive decay constant for material (hr^{-1})

$K'\epsilon_r$ = recirculation loop parameters (hr^{-1})

R = building infiltration factor (hr^{-1}).

The following assumptions are made to simplify Equation 22:

1) Radioactive decay is neglected. This simplification causes doses to be slightly overpredicted, especially for radionuclides with very short half-lives.
2) Deposition in ventilation ducting is neglected. This is justified by noting that duct velocities are high, resulting in significant re-entrainment of deposited or plated-out materia' and also that the residence time of any given particle in ducting is small compared to its residence time in a room where air velocities are low and settling can more readily occur. Thus, $K'\epsilon_r = 0$.
3) A deposition factor of .3 is used based on a 3 meter room height, a deposition velocity of 1.5×10^{-2} cm/sec, and a total surface area equal to 2.5 times floor area.[4]
4) A value of .85 is assumed for F.[4]
5) R is allowed to vary with building type as discussed in Appendix A.

Incorporating these assumptions, Equation 22 becomes

$$\frac{\phi_i}{\phi_o} = \frac{0.85}{1+0.3/R} \quad . \tag{23}$$

This ratio, referred to as the building dose factor (BDF), includes integration of both doses over all time, such that the exponential "tail" of material which remains inside the building after the cloud has left the area is also included.

5.1.3.1 Individual Doses

Building ventilation systems can be characterized in one of two ways: top intake or continuous intake. The top intake system is defined as a system in which the entire building is served by a central air conditioning system whose intake is located on the roof, and which maintains the building at a positive pressure so that infiltration through windows, doors, walls or cracks can be ignored as an intake source. This model might be characteristic of late-model high-rise buildings with unopenable windows. The cloud of debris would have to diffuse to the top of any building of this type before a non-zero interior concentration would be achievable. Since the assumption is that the building is served by a single central air-conditioning system, each person in the building would receive the same dose, regardless of floor.

The second case is referred to as continuous intake. This simply means that the building has openable windows and/or floor-by-floor air-circulating equipment (window-mounted units, fans, etc.). In this case, the dose received is similar to that for an individual exposed in a top-intake building, except the dilution factor would correspond to the outside concentration at the height of the particular floor. The dispersion model provides concentrations graded in vertical segments, so the doses would be different from floor-to-floor only if the building height were such that the various floors were exposed to different concentrations.

The individual doses received by people in buildings were computed using a version of Equation 17 which adds BDF, and uses the appropriate DF, considering the type of building ventilation system.

3.1.3.2 Integrated Doses.

The number of people exposed to a given concentration will either be the number of people in the building, or the number of people per floor, depending on the ventilation system. It is possible, therefore, to calculate integrated doses for a given accident in a given cell. First, the expression for dose to people in buildings with top ventilation systems:

$$ID = \sum_{k=1}^{t} PPB * \phi_{T,k}, \tag{24}$$

where PPB = people per building

$_{T,k}$ = individual dose during k^{th} time step for top-intake ventilation assumption.

Second, the expression for dose to people in buildings with continuous ventilation systems:

$$ID = \sum_{i=1}^{n} \left[\sum_{k=1}^{b} \left\{ PPF * \phi_{c,k,i} \right\} \right], \tag{25}$$

where n = number of floors for building in cell

b = number of time steps

$_{C,k,i}$ = individual dose on ith floor during kth time step for continuous ventilation assumption.

The method used to calculate the total integrated dose to people inside buildings for an entire cloud passage can now be specified in a manner similar to that used in Equations 20 and 21 for pedestrians and people in vehicles. First, for top-intake buildings:

$$ID_T = [PPB_1 * \Delta T_s * K' * BDF_1 * RDF * \sum_{u=1}^{m} (DF_{1,u} * \gamma_u)] +$$

$$[\Delta T_L * K' * RDF * \sum_{w=1}^{q} \sum_{z=1}^{p} (PPB_{w,z} * \gamma_{w,z} * DF_{w,z} * BDF_z)], \quad (26)$$

and second, for continuous intake buildings,

$$ID_C = [PPF_1 * \Delta T_s * K' * BDF_1 * RDF * \sum_{i=1}^{n} \sum_{u=1}^{m} (DF_{i,u} * \gamma_{i,u}] +$$

$$[\Delta T_L * K' * RDF * \sum_{w=1}^{q} \sum_{t=1}^{p} (PPF_z * BDF_z * \sum_{i=1}^{n_p} (DF_{w,f} * \gamma_{w,z})] (27)$$

Note that, in both cases, the subscripted 1 in the short time step portion simply refers to the cell in which the release occurred and, in all four cases, the is the area fraction for the cloud in the particular vertical volume segment of interest.

5.2 Cloudshine Doses From Accidents Involving Dispersible Sources

It can be shown that for a specific isotope, the dose received due to immersion in a semi-infinite cloud for the period of cloud passage is directly related to the concentration of the material and the length of the exposure. Thus, the cloudshine dose received by an individual can be specified by

$$D = Q_6 * CDF * DF * \Delta T * n_2 * PPS * RF, \tag{28}$$

where Q_6 = units conversion factor

CDF = cloudshine dose factor (mrem/yr/ ci/ml).

By incorporating the building dose factor and the appropriate dilution factor, individual doses received by each population subgroup can be determined. Integrated doses are computed as before by summing over time-steps, and including person density and cloud area fraction (γ). In computing cloudshine doses to people in vehicles, no shielding is considered based on data provided in Reference 4. Values for CDF are given in Appendix A.

5.3 Dose Due to Material Remaining at the Scene of the Accident

In any accident, some fraction of the material remains at the accident site. This is referred to as the remnant material.

This material can be split into two groups: material which remains shielded, and material which escapes from the package but does not become airborne. The fraction of material which remains shielded inside the package is given by (1-RF), and the portion of material which is released from the package but does not become airborne is given by (RF)(1-AER). These two groups of material act as an exposure source identical to that discussed in Section 4.1 with a source term given by

$$\begin{aligned} K'' = {} & (Q_1 * n_2 * PPS * E_d * \mu * \{(RF)(1-AER)\}) + \\ & (K_o * TE * PPS * \{1-RF\}). \end{aligned} \tag{29}$$

Thus, substitution of this source term for k in Equations 4, 9, 12, 14, and 16 gives the dose for each of the population subgroups on each roadway type due to the material which remains at the site of an accident involving dispersible material.

6. Non-Release Vehicular Accidents

Most of the accidents involving transport vehicles are not severe enough to damage the package such that shielding is displaced or contents are released. However, these accidents may disable the vehicle sufficiently to cause it to remain in an area for an excessive period of time. If this situation were to occur, people in the area would receive additional exposure. This situation is analogous to the special-form source accident discussed earlier, except that the source term does not involve the curie content. Instead, the source term can be expressed as

$$K = K_o * TI * PPS. \tag{30}$$

Thus, the basic equations derived to evaluate accident-free exposures in Appendix D can be used to determine integrated doses to pedestrians, people in buildings, and people in vehicles. In addition to these population subgroups, crewmen would receive an additional dose by virtue of the delay time. This dose is specified as:

$$ID_{crew} = Q_3 * K * N_c * \frac{e^{-\mu_{air} d_2} B_{air}(d_2)}{d_2^2} * \Delta T_a \quad , \tag{31}$$

where N_c = number of crewmen

d_2 = source-to-crew distance (m).

7. Summation of Direct Radiological Effects Resulting from Accidents

Previous sections have discussed the determination of the population exposure consequences of specific accidents to individuals and to the overall population. This type of information is useful, but in order to make a final combination such that values can be compared from route-to-route or with accident-free impact, two further operations are necessary: conversion to expected number of health effects, and combination of release and nonrelease accident impacts for each mode and route. The value computed by these operations is referred to as the accident risk.

As discussed in Appendix H, the "common denominators" for a health effect comparison are early fatalities, early morbidities, latent cancer fatalities, and genetic effects. Use of these parameters allows one to quantitatively compare population doses to various organs, and to compare external whole-body radiation to doses resulting from inhalation of radioactive material.

Values for individual dose can be converted to expected numbers of early fatalities by multiplying the individual doses by the probability of fatality given the dose, and then summing over the various computed individual doses received:

$$\begin{pmatrix}\text{Expected number of}\\ \text{early fatalities}\\ \text{per accident}\end{pmatrix} = \sum^{\eta}\sum^{\phi} N(D_f) * P(D_f), \tag{32}$$

where η = number of fatality types evaluated

$N(D_f)$ = number of people receiving dose D_f in the given accident

$P(D_f)$ = probability of early fatality, given dose D_f.

The early fatality probabilities are provided for a set of discrete dose intervals, and the people exposed in each of these intervals are assigned the probability of early fatality associated with the lowest dose in the interval.

Early morbidities are handled slightly differently because they are evaluated on the basis of exceeding a threshold:

$$\text{Expected number of early morbidities per accident} = \sum^{\eta} N'(D_m), \tag{33}$$

where η = number of morbidity types evaluated

$N'(D_m)$ = number of people receiving dose D_m or greater in the given accident where D_m is the threshold dose for the specific biological effect.

Each computed integrated dose can be converted to a value for expected number of latent cancer fatalities or genetic effects by multiplying the integrated organ dose by its appropriate coefficient. First, however, the integrated exposure associated with persons who suffer early fatalities is subtracted from the total. The remaining person-rem can be converted as shown.

$$\left(\begin{array}{c}\text{Expected number of}\\ \text{long-term effects}\\ \text{per accident}\end{array}\right) = \sum_{s} (ID_s * CF_s * DEF) \quad , \tag{34}$$

where s = index over various organs

ID_s = integrated population dose to the s^{th} organ received in specific accident (less that received by persons who are early fatalities)

CF_s = health effect coefficient for s^{th} organ for health effect of interest (see Appendix H)

DEF = dose-rate effectiveness factor (see Appendix H).

Once the expected number of consequences per accident has been evaluated, a value for risk can be computed. The expected values for health effects computed in Equations 32, 33, and 34 are only for accidents of a specific severity occurring in a specific cell along the route. Accidents of other severities occurring in other cells must now be considered. Since consequence-per-route is expressed in terms of expected numbers of health effects, the occurrence rate for each severity class of accidents must be considered. Accident rates may show significant variation from cell-to-cell or from time-span to time-span. If T_z is the time at which the shipment would be at the center of cell z, the expected number of accidents of severity g in cell z is given by

$$\epsilon_{z,g} = L_z * AR_z * e_{g,z}, \tag{35}$$

where g = index over accident severities

L_z = the distance traveled in cell p

AR_z = accident rate per unit distance (dependent upon time-span when transport occurred) mode dependent.

$e_{g,z}$ = fraction of accidents of severity g in cell z

This can be combined with earlier expressions to give the total expected number of health effects from transport along a specific route:

$$\text{Total expected health effects} = \sum_{z=1}^{H} \sum_{g=1}^{\theta} \text{Effect}_{z,g} * \epsilon_{z,g} , \tag{36}$$

where H = number of cells along route

θ = number of accident severity categories

$Effects_{z,g}$ = expected number of effects from accident of severity g in cell z during time span of interest (sum of values from Equations 31, 32, 33)

$\epsilon_{z,g}$ = expected number of accidents of severity g in cell z per trip through grid (Equation 34).

8. Decontamination Impact Model

The radioactive contamination which can result from an accident involving a release of a dispersible radionuclide may cause a significant economic and/or social impact.[1] An estimate of the costs associated with this aspect is discussed below.

Land-use information for each cell in the grid must be available. This information takes the form of fractions representing the amount of area devoted to high-rise buildings, single-family units, parks, streets, industrial areas, etc. Data[1-5] can then be used to assess the costs of decontaminating the various portions of each affected cell. In addition to outright cleanup costs, costs of evacuation, loss of income, and security force costs are also computed.

Two contamination levels are considered based on the decontamination factor, df*, required: heavy contamination (df $\geq$ 20), and low-level contamination (df < 20), because different techniques (and, therefore, different costs) are associated with cleanup

*The decontamination factor is defined as the ratio of the contamination level before cleanup to the level of the contaminant after cleanup.

involving different levels of contamination. The area contaminated to each level for each cell is specified by the surface deposition portion of the meteorological dispersion model, using a source term based on the amount of material transported, the accident severity, and the package release model.

Addendum I

Variables, Constants, and Functions Used in Appendix E

Table 1. List of Variables

Symbol	Description	Units	Equations
DR	dose rate	mrem/hr	1
n_2	number of curies per package	curies	1,3,17,28
PPS	number of packages per shipment	-------	1,3,17,18,28,29,30
RF	release fraction	-------	1,3,17,28
E_d	total photon energy per disintegration	MeV	1,3,29
μ, μ_{air}, μ_b	linear attenuation coefficient	m^{-1}	1,2,3,4,5,9,10,14, 16,29,31
r	distance from source	m	1,2,5,9,14,16
K, K', K''	direct exposure source term	mrem-m^2/hr	2,3,4,5,9,10,11,12, 14,15,16,29,30,31
ΔT_a	accident delay time	hr	2,4,5,9,10,11,12, 14,15,16,31
$\phi, \phi_{inh}, \phi_T, dc$ i, o	individual absorbed dose	rem,mrem	2,5,17,19,22,23,24, 25
K_o	package shape factor	mrem-m^2/hr	3,29,30
TI	transport index	-----	3,29,30
PedD	pedestrian density	persons/km^2	4,19,20
w_{st}	street width	m	4,7,8,9,10,11,12,13
w_s	sidewalk width	m	4,9
x,y	perpendicular distances from source	m	4
ID, ID_{bldg}, ID_{inh}, ID_{veh}, ID_{crew}, ID_T, ID_C, ID_s	integrated dose	person-rem	4,9,10,11,12,14,15, 16,19,20,21,24,25, 26,27,31,34
w_b	building wall thickness	m	5,9,14

Table 1 (cont'd.)

Symbol	Description	Units	Equation
PPW	persons per wall	-----	6,7
PPF	persons per floor	-----	6,8,9,13,14,25,27
PPB	people per building	-----	24,26
A	cell area	m^2, km^2	7,8,9,13,14
L, L_z	distance traveled in cell	m	7,8,9,13,14,35
f_b	fraction of cell area occupied by buildings	-----	7,8,9,13,14
f_{st}	fraction of cell area occupied by streets	-----	7,8,9,13,14
PPL	people per unit length	persons/m	7
n	number of floors	-----	9,14,25,27
i	summation index over floors	-----	9,14,25,27
h	height per floor	m	9,14
PPV	people per vehicle	persons	10,11,12,15,16,21
L'	number of lanes per side of the street	-----	10,11,12
δ	vehicle separation while stopped	m	10,11,12,15,16
ℓ	vehicle length	m	10,11,12,15,16
j	summation index over vehicles	-----	10,11,12
E'	surrogate summation limit	m	12
w_f	freeway width	m	14,16
β_1, β_2	surrogate integration limit	m	9,14
f_f	freeway bunching factor	-----	15,16
N_f	one-way freeway traffic count	vehicles/hr	16
V_f	freeway velocity	m/sec	16

Table 1 (cont'd.)

Symbol	Description	Units	Equation
AER	fraction of released material which is aerosolized	-----	17,18,29
RESP	fraction of aerosolized material which is respirable	-----	17,18
RPC	dose per curie deposited in pulmonary compartment of lung	rem/curie	17,18
E	particle size adjustment factor	-----	17,18
DF	dilution factor	$ci/m^3/ci$ released	17,18,20,21,26,27,28
BR	breathing rate	m^3/sec	17,18
ΔT	time step length (general)	hr	17,18,28
K'	inhalation dose source term	rem-m^3/sec	18,20,21,26,27
t	number of time steps (general)	-----	18,19,24
k	summation variable over time steps (general)	-----	18,24,25
Y	fraction of cell covered by cloud	-----	19,20,21,26,27
RDF	resuspension dose factor	-----	19,20,21,26,27
ΔT_s	length of short time step	hr	20,21,26,27
ΔT_L	length of long time step	hr	20,21,26,27

Table 1 (cont'd.)

Symbol	Description	Units	Equation
m	number of short time steps	-----	20,21,26,27
u	summation variable over short time steps	-----	20,21,26,27
q	number of long time steps	-----	20,21,26,27
w	summation variable over long time steps	-----	20,21,26,27
z	summation variable over cells	-----	20,21,26,27,35
p	number of cells in grid	-----	20,21,26,27
N'	total vehicles per cell	veh/km^2	21
R	air change rate	changes/hr	22,23
b	number of time steps (general)	-----	25
F	filtration factor	-----	22
D_1	deposition factor	hr^{-1}	22
λ	radioactive decay constant	hr^{-1}	22
$k'\varepsilon_r$	recirculation loop parameters	hr^{-1}	22
CDF	cloudshine dose factor	-----	8
N_c	number of crewmen	-----	31
d_2	source-to-crew distance	m	31
D_f, D_m	dose for fatalities or morbidities	rem	32,33
CF	long-term health effect coefficient	health effects/ 10^6 person-rem	34
DEF	dose-rate effectiveness factor	-----	34

Table 1 (cont'd.)

Symbol	Description	Units	Equations
s	summation index over organs	-----	34
$N(D_f)$	number of people receiving dose D	-----	32
$P(D_f)$	probability of early effect given dose D	-----	32
$N'(D_m)$	number of people receiving dose D or greater	-----	33
AR_z	accident rate	accidents/km	35
e_g	fraction of accidents of severity g	-----	35
$\varepsilon_{z,r}$	expected number of accidents of severity g in cell z	-----	35,36
g	summation index over severity categories	-----	35,36
H	number of cells along route	-----	36
θ	number of accident categories	-----	18,36
BDF	building dose factor	-----	26,27
η	number of health effect types (morbidities/ mortalities)	-----	32,33

List of Constants

Symbol	Value	Units	Equations
Q_1	147	$\frac{\text{mrem-m}}{\text{hr-curie-MeV}}$	1,3,29
Q_2	$1 * 10^{-9}$	$\frac{\text{rem-km}^2}{\text{mrem-m}^2}$	4
Q_3	10^{-3}	$\frac{\text{rem}}{\text{mrem}}$	9,10,11,12,14,31
Q_4	$2.78 * 10^{-7}$	$\frac{\text{rem-hr}}{\text{mrem-sec}}$	15,16
Q_5	$2.78 * 10^{-4}$	$\frac{\text{hr}}{\text{sec}}$	16
Q_6	$1.14 * 10^{-7}$	$\frac{\text{rem-yr-}\mu\text{ci/ml}}{\text{mrem-hr-ci/m}^3}$	28

Table 3

List of Functions

Symbol	Description	Equations
$B(r)$, $B_{air}(r)$, $B_b(w_b)$	dose buildup factor	1,2,4,5,9,14,16,31
$OF(r)$	obliqueness factor	5,9,14

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APPENDIX F

MICMET - Small Scale Atmospheric Transport Model

1. Introduction

In order to predict the air concentrations of radioactive material within a short distance (one or two city blocks) of the point of release due to an accident, a model utilizing a plume element technique[1] was formulated. This model, called MICMET, was specifically developed to provide appropriate airborne concentrations, owing to a puff release, to both the radiological consequences model (METRAN) and the larger scale atmospheric transport model (PICMET). Therefore, while the techniques used in MICMET are general, the model itself is tailored to specific requirements of these two other models.

2. General Approach

The initial condition for the model is assumed to be a stabilized cloud of radioactive material created by some form of accident. The height of this stabilized cloud is supplied as an input parameter. The diameter of the cloud is assumed to be 20% of the height and constant as a function of height. These choices for the characteristics of the stabilized cloud are based on data from atmospheric explosive detonations, and estimates of possible release conditions in an accident. The stabilized cloud is divided into a number of layers, or plume elements, to allow for variations with height of wind speed, and turbulent mixing characteristics.

The vertical variation of mean horizontal wind speed is calculated for the grid cell in which the release is assumed to occur. Parameters which are included in the data base (Appendix A) are used in this calculation to provide realistic wind speeds and cloud standard deviations for the plume element technique.

The model treats selected aspects of flow in urban areas in a predominantly qualitative manner. A detailed quantitative analysis of flow in an urban area on the scale of individual streets has been undertaken in the past[2] but the techniques employed are too complex and costly to be used in the present study. Some aspects of the flow over an urban area are included in the calculation of the mean velocity profiles. The details of these calculations are presented in Section 3 of this appendix. In some instances, restrictions are placed on the direction of travel and rate of growth of the cloud, based upon the size and orientation of the street canyon relative to the initial stabilized cloud. These restrictions, and the cases for which they are assumed to apply, are discussed in Section 4 of this appendix.

3. Vertical Velocity Profile Calculations

The data base used in the assessment includes a mean horizontal wind speed at a height of 30 m. This value is used in conjunction with data concerning the density and height of buildings to compute the parameters which are included in the logarithmic expression for the vertical variation in mean horizontal velocity

velocity profile).[3] The velocity profile at heights below that of the average building is described using an exponential relationship initially developed to describe canopy flow, and which has also been applied to describe flow below mean building height in an urban area.[4]

The logarithmic expression for the velocity profile above building height takes the following form:

$$u(z) = \frac{\bar{u}_*}{k} \ln \frac{z + z_o + d}{z_o} \quad , \tag{1}$$

where

$\bar{u}(z)$ = mean horizontal velocity at height z

u_* = surface friction or shear velocity

k = von Karman constant (0.38 - 0.40)

z = vertical coordinate

z_o = surface roughness length

d = displacement height.

This form of a logarithmic profile does not include any effects of atmospheric stability. The available data base did not provide sufficient information to estimate atmospheric stability, although it would be possible to include effects of atmospheric stability in the logarithmic formulation.

Values of z_o and d are computed for an urban area using expressions developed by Lettau[5]:

$$z_o = \frac{h_b S}{2S_\ell} \tag{2}$$

$$d = z_o x - (h_b + z_o) \tag{3}$$

$$x \ln x = 0.1\ h_b^2/z_o^2 \quad , \tag{4}$$

where

h_b = average building height in grid cell

S = average silhouette area

S_ℓ = average lot area

x = intermediate value used in calculation of displacement height.

For the application of these expressions to a large urban area, a minimum value of z_o of 0.2 m has been assumed. The values of z_o, d, and $\overline{u}(30)$ are used in Equation 1 to calculate u_*. Equation 1 can then be used to evaluate the mean velocity at any height above building level.

For elevations below the average building height, an exponential expression is applied[4]:

$$\overline{u}(z) = U_o e^{z/A_1} \ , \tag{5}$$

where

$$A = \frac{0.1\ h_b^2}{z_o} \quad . \tag{6}$$

If in a particular cell, h_b is less than 30 m, U_o is evaluated by equating $\overline{u}(h_b)$ in Equations 5 and 1. When h_b is greater than 30 m, U_o is computed from the input data for that cell, and u_* is computed by matching Equations 1 and 5 at $z = h_b$.

4. Plume Element Dispersion Model

4.1 Model Description

A layered Gaussian or plume element[1] technic   is the basis of MICMET. The initial stabilized cloud is divided into a number of horizontal layers. Each layer is transported by the mean velocity corresponding to the initial height of the layer, and allowed to grow in the along-wind, across-wind and vertical directions. The standard deviations, or σ's, used in the Gaussian formulation are calculated as a function of downwind travel distance and turbulence intensity using a relationship provided by Pasquill[6]

$$\sigma_j = 2/9 \; i_j x \quad , \tag{7}$$

where x is the downwind travel distance, i_j is the turbulence intensity in the jth coordinate direction, and σ_j is the standard deviation of cloud concentration in the jth coordinate direction. The model allows particles to fall with a velocity based on their assumed diameter. Deposition is considered on horizontal surfaces only. These surfaces may be specified as perfectly reflecting, perfectly absorbing, or any intermediate situation.

Normalized airborne concentrations (the concentration per unit of radiocative material released) are calculated as a function of time and position. Because the resultant cloud is assumed to travel through an urban area, the concentration is evaluated as a function of space as well as time. This approach is somewhat more complex than consideration of averaged near ground-level airborne concentrations.

While the initial cloud size and number of layers or plume elements used are variable, present results have utilized 5 layers and a stabilized cloud top height of 10 m.

4.2 Model Cases and Constraints

The model has two modes of operation based upon the stabilized height of the initial cloud, relative to the average height of the buildings in the cell of release. If the stabilized height of the initial cloud is greater than the average building height in the cell of release, the cloud is allowed to travel in the direction of the mean wind. The effects of the urban area on the transport and dispersion of the cloud are included through the mean velocity profile and standard deviations of layer growth through Equations 2, 3, and 7.

If the stabilized height of the initial cloud is less than the average building height in the cell of release, two release locations are provided for selection: a release at an intersection, or a release in the center of a block, midway between two intersections. For a release at an intersection, the cloud is constrained to travel along the streets downwind of the intersection. Either one or two clouds may result. The selection of the number of clouds is based on the relative orientation of the direction of the mean wind and the streets in the region of interest. If there is greater than a 10-degree difference between the mean wind direction and the nearest downwind street direction, two clouds are used in the calculation. The amount of material allocated to each cloud is proportional to the complement of the angle between the wind direction and the street of interest. For the first block of travel, the lateral growth of the cloud is limited by the width of the street. After the first block of travel, the lateral growth of the cloud is allowed to resume, although the direction of travel remains constrained by the orientation of the street. These assumptions involving direction of cloud travel and restriction of lateral cloud growth are considered to be valid only a short distance from release (~2 or 3 blocks). In the present application of the model, the cloud is allowed to travel less than 2 block-lengths before the responsibility for the transport calculation is transferred to PICMET, the model developed to deal with scales larger than MICMET.

If the release is assumed to occur at the center of the block, two situations are considered. The first occurs when the mean wind direction is within 30 degrees of the street in which the release occurs. In this situation, the cloud is constrained to travel along the street as discussed in the preceding paragraph. When there is greater than a 30-degree difference between the mean wind direction and the street, full-scale measurements indicate a vortex flow is developed in the street canyon.[7] In such a case, a flushing time is computed based on a technique developed by Nicholson.[4] A single cloud the size of the street canyon, one block long, and of uniform concentration, is provided as input to PICMET after the flushing time has elapsed.

4.3 Output of the Model

While MICMET can provide an air-borne concentration as a function of both space and time, the desired output to be used in both PICMET and METRAN (the radiological consequences model) dictates the use of a more concise description of the resultant cloud, as a function of time. At specified time-steps, the resultant spatial air-borne concentrations from all source layers are integrated to obtain the centroid and standard deviations of the resultant cloud. These parameters are than supplied to either METRAN or PICMET as required.

5. Interface of MICMET With PICMET And METRAN

In the present configuration, MICMET is only used for the first 300 m of travel of the centroid of the resultant cloud. The time required for the cloud to reach this position is divided into four equal intervals. At the end of each of these intervals, the centroid and standard deviations of the cloud (or clouds) are provided to METRAN for direct use in the health effects model. At the end of the fourth step, the centroid and standard deviations of the cloud (or clouds) are used to load particles into PICMET as initial conditions.

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APPENDIX G

PICMET - The Urban-Regional Atmospheric Transport Model

1. Introduction

The urban-regional atmospheric transport model, PICMET, was designed to estimate the transport and atmospheric diffusion of radioactive material that might be released in a puff as a result of an accident in an urban area. The initial evolution of the puff release is estimated by a small-scale atmospheric transport model, MICMET, described in Appendix F. After the cloud has moved several hundred meters from the release point, the MICMET model supplies initial conditions for PICMET, which follow the dispersal of the released material over distances on the order of tens of kilometers, or out to arbitrarily defined boundaries of the urban region under study. Like the small-scale transport model, PICMET supplies estimates of the normalized air concentration (concentration per unit of material released) of the radioactive material to the radiological consequences model, METRAN, at the end of prescribed time intervals.

This appendix provides a short description of PICMET, emphasizing special techniques used in the model. A similar approach to atmospheric transport and diffusion using a combination of small-scale and regional transport models has been recently applied by Sheih[1] to the study of pollutant transport over an urban area.

2. General Approach

The estimation of transport and atmospheric diffusion in PICMET is accomplished by numerically solving the atmospheric diffusion equation,[2] using a modified particle-in-cell (PIC) technique.[3]

The mathematical basis for solving the equation in question by PIC techniques is summarized by Sklarew, et al.[4,5]

The atmospheric diffusion equation is solved on a three-dimensional array of cells that cover the urban region. All cells must have the same dimensions; but cell dimensions and the number of cells used to cover the region can be chosen by the model user. A mean wind velocity and three components of eddy diffusivity must be prescribed at the center of each cell. In addition, the boundary conditions that apply at the vertical sides, the top surface, and the bottom surface (ground level) of the cell array must be specified.

Within the boundaries of the cell array, PICMET follows the motion of a large number, N, of Lagrangian particles, each of which is assumed to carry a fraction, 1/N, of the released material. These Lagrangian particles are initially positioned in the cell array with a density proportional to the normalized concentration of air-borne material provided by the MICMET model. The particles are subsequently moved in short time-steps along trajectories appropriate to the combined mean wind and turbulent flux velocity fields. The simulated transport is terminated when all but three of the Lagrangian particles have passed through the boundaries of the region, or when surface deposition has depleted the clouds to a degree that air-borne transport is no longer judged to be significant.

3. Calculation of Wind Fields and Eddy Diffusivities

The mean wind field and eddy diffusivities are constructed from available data dealing with the horizontal mean wind field (usually measured at a fixed reference height above the ground), the mean building height, and the fraction of land occupied by structures. These data are included in the data base discussed in Appendix A.

A vertical profile of horizontal mean wind velocity is calculated for the surface layer overlying each base cell, using the same formulae as those used to obtain vertical velocity profiles in MICMET (see Appendix F, Section 3). The stratified horizontal winds obtained are then made divergence-free at each cell center by the addition of an appropriate, usually small, vertical component of wind. Finally, a free-fall speed is added to the vertical component of wind in all the cells. The free-fall speed depends on the average size of the small particles that may constitute the released material, i.e.,

$$w_{\text{free-fall}} = -1.26 \times 10^{-3} \, D^2 \text{ km hr}^{-1},$$

where D is the particle diameter in μm.

The data on horizontal mean wind at reference height, the average building height, and the fraction of land occupied by structures are also used to determine the profile of the vertical component of eddy diffusivity, K_z, by formulae given in Ragland and Peirce.[6] An adiabatic atmospheric surface layer is assumed in the model so that

$$K_z = 0.4 \, u_* z \;,$$

where u_* is the surface friction or shear velocity (computed in the same way employed for MICMET; see Appendix F, Section 3), and z is the height above ground level. In the absence of empirical information on the relative magnitudes of the horizontal eddy diffusivities (K_x and K_y) in an urban setting, we have arbitrarily assumed that K_x and K_y are proportional to K_z.

4. Boundary Conditions and Surface Depositions

There are several kinds of boundary conditions in the PICMET model. The vertical sides and top surface of the cell array are assumed to be transmitting boundaries; that is, material is allowed to flow freely across the boundary and is subsequently removed from the cell array. The lower boundary of the cell array (ground level) can be anything between a reflecting boundary and a completely absorbing boundary, depending upon a coefficient of surface absorption, α, $0 \leq \alpha \leq 1$, that can be assigned to each ground level cell. To assure conservation of mass in the implementation of these boundary conditions, and to calculate surface deposition, the concept of particle weighting* is used. A particle weight, P, initially = 1/N, is assigned to each of the N Lagrangian particles employed in the simulation. The particle weight never changes unless the particle is dropped from the set after crossing a transmitting or perfectly absorbing ($\alpha = 1$) boundary or the particle crosses a partially absorbing boundary ($0 < \alpha < 1$). In the latter case, the particle is not dropped, but is physically reflected as though the boundary were

* Both particle weighting and <u>volume weighting</u> are used in PICMET. Volume weighting is a standard technique in PIC calculations. See Reference 4, for example.

perfectly reflecting ($\alpha = 0$). However, the reflected particle's weight is multiplied by $(1 - \alpha)$, and it is assumed that a fraction, αP, of the released material has been deposited on horizontal surfaces during the time-step and within the cell where the particle crossed the boundary. The particle weights are used to calculate the normalized, volumetric concentrations of the airborne material in a mass-conserving way.

5. Special Features of PICMET

When applied to the atmospheric diffusion equation, the standard PIC techniques[4,5] underestimate the rate of turbulent diffusion in material clouds whose characteristic sizes are small compared to cell dimensions. The source of trouble is the finite-difference approximations made for computing the three components of turbulent flux velocity:

$$u_f = -\frac{K_x}{C}\frac{\delta C}{\delta x} \qquad v_f = -\frac{K_y}{C}\frac{\delta C}{\delta y}, \quad w_f = -\frac{K_z}{C}\frac{\delta C}{\delta z}\,. \tag{1}$$

Until material has spread through several cells, a finite difference approximation to the concentration derivatives of Equation 1 will give unphysical, small turbulent flux velocities, thereby inhibiting expansion of the cloud.

There are several techniques available for use in place of finite-differences that give better approximations to the field of turbulent flux velocity in small clouds. Two of these techniques used in PICMET are described below.

A. Treatment of Horizontal Turbulent Flux Velocity

As an alternative to the finite-difference approximation of the horizontal turbulent flux velocity, u_f and v_f, of Equation 1, an analytic calculation of these quantities is made in which the instantaneous concentration field of suspended material is assumed to have a horizontal (x,y) Gaussian distribution. The centroid coordinates $(\bar{x},\bar{y})$, and the standard deviations, (σ_x, σ_y), of the Gaussian are computed from the positions of the weighted particles. For instance,

$$\bar{x} \equiv \frac{\sum_i P_i \; x_i}{\sum_i P_i}$$

$$\sigma_x^{\;2} \equiv \frac{\sum_i P_i \; (\bar{x} - x_i)^2}{\sum_i P_i} \quad , \tag{2}$$

where x_i is the x-coordinate of the i^{th} particle in the mesh, P_i is the weight of the i^{th} particle (see Section 4, this appendix), and the sums run over all particles in a single cloud. The turbulent flux velocities are obtained by analytical differentiation of the Gaussian, according to the expressions for u_f and v_f given in Equation 1. The results are:

$$u_f = \frac{K_x}{\sigma_x^{\;2}} (X_i - \bar{X}), \quad v_f = \frac{K_y}{\sigma_y^{\;2}} (y_i - \bar{y}) \; . \tag{3}$$

These velocity components are added to the corresponding components of the mean horizontal wind, $(\bar{u}, \bar{v})$, taken at the position of the i^{th} particle, to get the total horizontal velocity of that Lagrangian particle. The technique is computationally inexpensive, but it requires that the particles comprising each cloud be distinguished so that the centroids and standard deviations for each cloud may be calculated.

Figure 1 shows results of the two different treatments of horizontal diffusion in a single cloud. The standard deviation in cloud size along the Y-direction, σ_y, is plotted as a function of distance from the release point. The curve marked "(3)" was calculated using the approximation leading to Equation 3. The dashed curve, marked "(FD)," was calculated using the finite difference approximation for the turbulent flux velocities. In each case, the empirical standard deviation of the particle cloud, given in Equation 2, is plotted against the absolute displacement distance of the cloud centroid after handover by MICMET (see Appendix F). For the comparison, a wind speed at reference height (30 m) of 1 m/s was chosen. The wind is uniformly directed along the positive X-axis.

Also shown in Figure 1 are the limiting curves of σ_y versus distance expected for the range of Pasquill turbulence types.[7] Note the unphysical behavior of the finite-difference approximation when the characteristic, horizontal size of the cloud is less than one cell dimension.

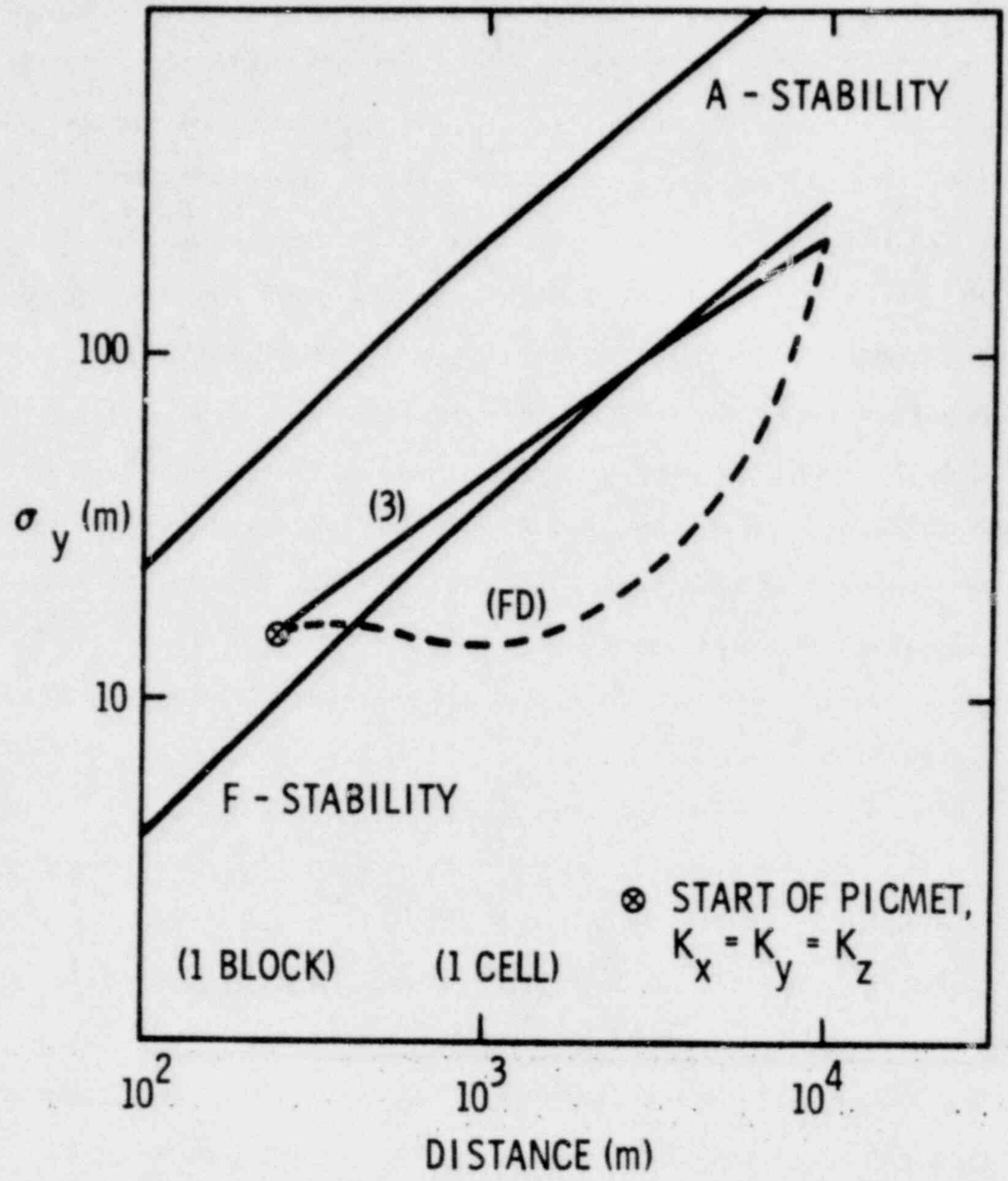

Figure 1. Comparison of Different Treatments of Horizontal Diffusion

B. Treatment of Vertical Turbulent Diffusion

The vertical distribution of material in the cloud is not likely to be Gaussian because of constraining effects of the ground surface. Thus, a treatment of the vertical component of turbulent flux velocity in a manner similar to the one described in Section A above, is not always possible. Instead, PICMET uses a technique employed by Schwartz[8] to numerically solve an equation of the same form as the atmospheric diffusion equation. Because this technique can be computationally expensive, it is only applied in PICMET to the vertical component of turbulent diffusion. This is accomplished as follows:

In each time step, each Lagrangian particle is displaced by an amount,

$$\bar{w}(i)\Delta t + \xi_i ,$$

where $\bar{w}(i)$ is the mean vertical wind speed (plus constant particle settling velocity) measured at the position of the i^{th} particle; Δt is the length of the time-step, and ξ_i is a random displacement drawn from a normal distribution whose mean is zero and whose standard deviation is

$$[2K_z(i)\Delta t]^{1/2} ,$$

where $K_z(i)$ is the vertical component of eddy diffusivity measured at the location of the i^{th} particle.

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APPENDIX H

Radiological Health Effects

1. Introduction

Biological effects of radiation are a manifestation of the localized deposition of energy in molecules along the path traveled by the radiation. The ionizations and excitations caused by this deposition can directly or indirectly alter both the chemical composition, and the chemical equilibrium within tissue cells along the path of the radiation.[1] The possible effects of this energy deposition range from undetectable changes to acute physiological changes, carcinogenesis, or genetic effects, depending on the amount and type of incident radiation, the type of cells irradiated, and the time span over which irradiation occurs. These effects have been the subject of considerable research since the early part of the twentieth century. This appendix will not attempt to discuss in detail the extensive literature which exists on this work, but will summarize those aspects of radiological health effects which are used in the environmental assessment of the transportation of radioactive materials in and around urban areas.

2. Specific Radiological Health Effects

2.1 Acute Physiological Changes

Acute physiological changes due to radiation exposure are normally associated with relatively large absorbed doses received over a short period of time. Data on these effects in humans are derived largely from studies of Japanese atomic bomb casualties,[2] studies of some radiation therapy patients,[3] and studies of a few recipients of high acute doses from industrial accidents in the early days of the nuclear weapons development program.[4]

The acute physiological changes of interest in evaluating the potential environmental impact of transportation of radioactive materials can be divided into two groups: early morbidities and early fatalities. These effects are defined somewhat arbitrarily as those whose onset occurs within 1 year of the radiation exposure in question.[5] Two mechanisms are considered for early fatality: acute bone marrow irradiation and acute pulmonary irradiation. Acute gastrointestinal exposure could also cause early fatalities but, as explained in Section 3.1 of this appendix, this early fatality mechanism is not considered. The dose-response curves for the two early fatality possibilities evaluated are shown in Figures 1 and 2. The derivation of the curves including experiments involved and uncertainties, is discussed in Reference 5.

Early morbidities are analyzed in a somewhat more qualitative fashion because the effects of sublethal doses are not as well understood.[5] The approach taken in this assessment is to compute the number of people receiving greater than some morbidity threshold dose to a particular organ or system (e.g., bone marrow). These thresholds represent acute doses above which some type of debilitating radiation syndrome is possible. This group of people could be referred to as "potential radiation-induced morbidities." Latent cancer fatalities which might occur in this group are not considered separately, and synergistic effects between organ doses or between radiation exposures and other effects, such as old age or poor health, are not considered. This procedure clearly produces some "double accounting," but it should have a small effect on the final estimates of early morbidities. Values for morbidity thresholds for various organs are given in Table 1.

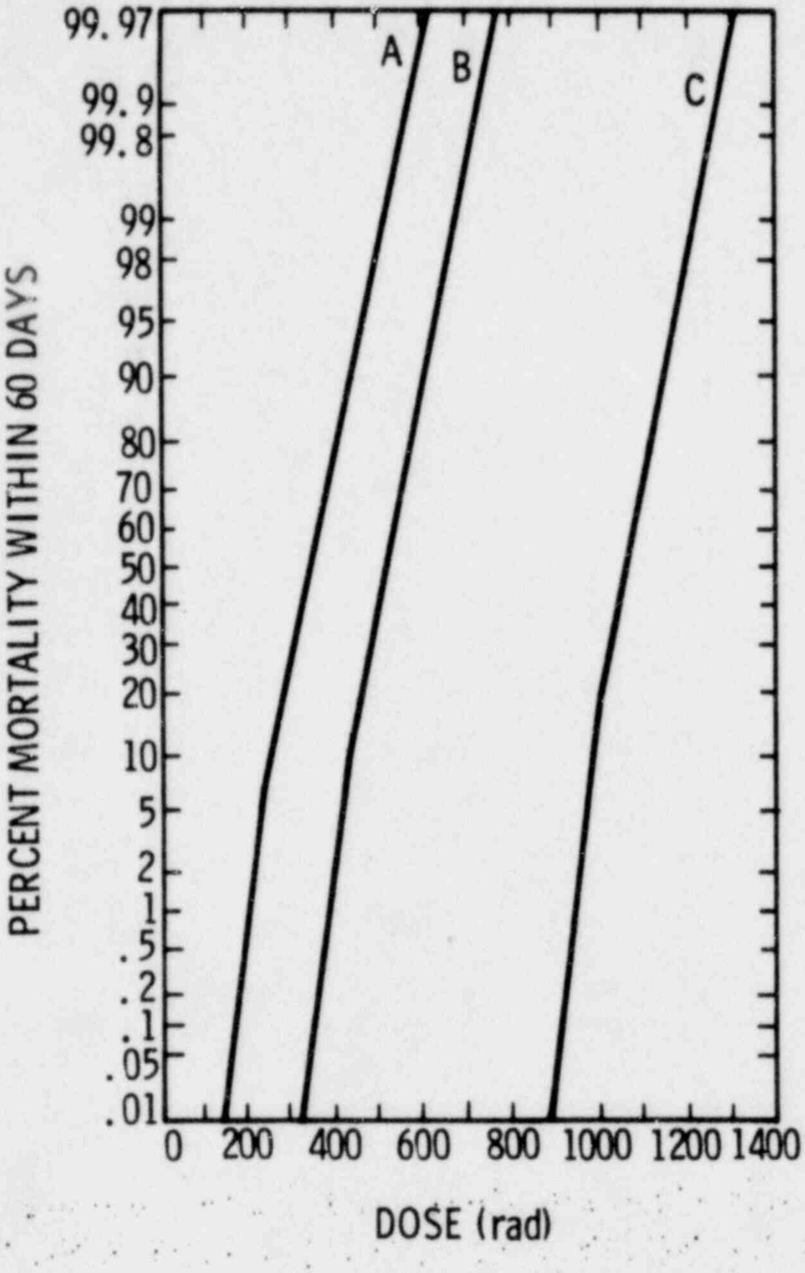

Figure 1. Estimated dose-response curves for mortality within 60 days from acute total bone marrow irradiation: with minimal treatment (curve A), supportive treatment (curve B), and heroic treatment (curve C)* (References 5 and 27).

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*minimal treatment - basic hospitalization.
supportive treatment - barrier nursing, antibiotics, transfusions.
heroic treatment - bone marrow transplants, etc.

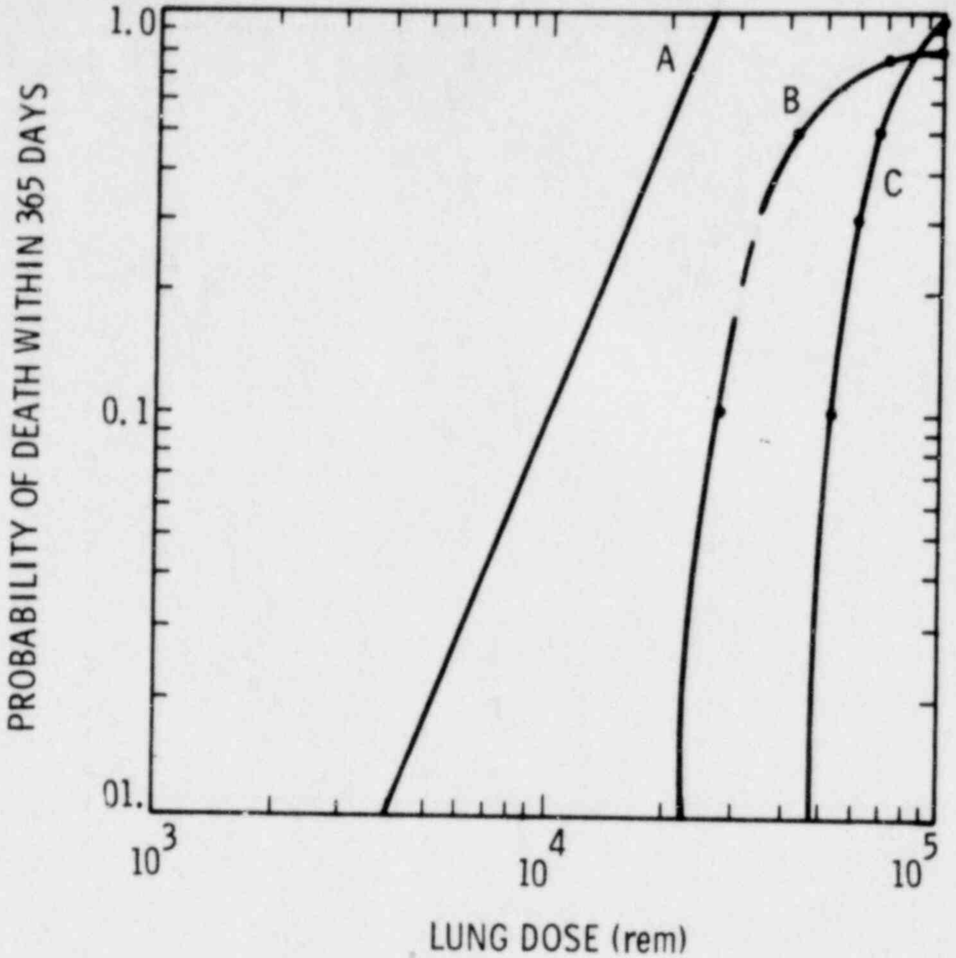

Figure 2. Dose response curves for mortality due to acute pulmonary effects of radiation

A. Yttrium-90 and -91 were the isotopes used to obtain this curve. It is equally valid for other short half-life beta or gamma emitting isotopes which result in approximately the same dose rate. This curve is used for all short half-life materials potentially encountered in transportation accidents. (Source - Reference 5)

B. This curve is based on data using Sr-90/Y-90 inhalation by beagles, and is used for long half-life, low LET* radiation (Source - Reference 37)

C. This curve is based on data from Pu-239 inhalation by beagles, and is used for long half-life, high LET* radiation (Source - Reference 37).

*LET (Linear Energy Transport) is a measure of the energy deposited per unit distance traveled in a particular medium. High LET radiation includes α-particles and fast neutrons; low LET radiation includes x-rays, γ-rays, and β-particles.

TABLE 1

MORBIDITY THRESHOLDS[5]

Organ	Threshold Dose (rem)	Physiological Result
Marrow	75	Radiation Syndrome*
Lung	3,000	Radiation Pneumonitis
GI Tract	1,000	Stem-cell Loss
Gonads	50	Transient Sterility

*Radiation syndrome is a group of symptoms which are normally associated with large acute whole-body exposures.

2.2 Long-Term Somatic and Genetic Effects

Both long-term somatic and genetic effects are evaluated. These effects are quantified using statistics from Reference 4 which relate expected occurrences to overall integrated population exposure.

There is considerable controversy surrounding the appropriate choice of risk models for the evaluation of radiation carcinogenesis. The choices involve the use of either a relative risk model or an absolute risk model. Relative risk is defined as "the ratio of the risk in those exposed to the risk to those not exposed (incidence in exposed populations to incidence in control populations)".[6] Absolute risk is defined as the "product of assumed risk times the total population at risk." The absolute risk model is used in this assessment since it provides a better indication than the relative risk model of the impact in terms of the total number of deaths in a population due to a disease. Cancer fatalities which occur in a given population are variable and may be influenced by many factors. In addition, a 30-year plateau is assumed for the period of risk, as compared to the lifetime plateau suggested by some individuals and organizations. These points of controversy will not be settled in the near future, and are acknowledged as important issues warranting further discussion and investigation. The net effect of using the relative risk model and a lifetime plateau would be to increase the estimates of latent cancer fatalities by less than an order of magnitude (roughly a factor of 7).

2.2.1 Carcinogenesis.

Fatal cancers account for between 16 and 20 percent of all deaths in the U.S.[7,8] These cancers are divided into three broad groups: carcinomas, sarcomas, and leukemias or lymphomas. Within these groups, there are 100 or so distinct varieties of disease based on the original site of the malignancy.

There are many theories of carcinogenesis, but most researchers acknowledge that a statistical correlation can be established between certain environmental factors and cancer induction. Examples include the correlation of smoking to lung cancer, and the correlation of radiation dose to leukemia among atomic bomb survivors. The correlation between exposure to radiation and cancer induction has been qualitatively established for animal exposures, and is generally accepted for human exposures, although the physiological mechanisms involved are not well understood.[6,9-11] Statistical analysis of large numbers of exposed personnel, such as Japanese atomic bomb survivors, uranium miners, fluorspar miners, radium dial painters, etc., permits crude predictions of numbers of latent cancer fatalities per million person-rem of population exposure. In general, this information is based on investigations using specific isotopes such as Ra-226. However, in this assessment and in other studies, the use of these values is expanded with the understanding that the effects of varying the nature of the radiation may alter the results.

In the quantification of carcinogenesis in this assessment, a modified version of the linear dose-response model is assumed. For doses received at dose rates less than 1 rem/day (~ 400 rem/year), a "dose-rate effectiveness factor" of 0.2 is assumed, based on conclusions extracted from Reference 5. For doses received at rates greater than 1 rem/day, a dose-rate effectiveness factor of 1.0 is assumed. This means that if a population s.gment receives a given total dose at a rate of less than 1 rem/day, the cancer induction rates in that population segment would be 20% of those predicted by the linear dose response model for a similar population segment receiving the same total dose at a rate of greater than 1 rem/day. For populations exposed to mixed dose rates, a population weighted dose rate effectiveness factor is used. Expected latent cancer fatalities for a specified integrated population exposure to various organs are shown in Table 2 for a dose-rate effectiveness factor of 1.0. A brief discussion of the origin of each of these values follows.

Leukemia. The source of data for expected leukemia fatalities from radiation is the BEIR Report[6] as modified by the age distribution of the U.S. population.[5] Thus, although the *in utero* leukemia death rate due to irradiation is much higher than the corresponding death rate for other age groups, the fraction of pregnant women in the general population is small, and the overall leukemia death rate is somewhat lower than the fetal rate alone. The computed value of 28.4 leukemia fatalities per 10^6 person-rem is consistent with values suggested for high dose rates in Reference 12.

TABLE 2

EXPECTED LATENT CANCER FATALITIES* PER 10^6 PERSON-REM EXPOSURE TO THE POPULATION[1,8,12]

Organ Exposed	Expected Deaths per 10^6 Person-Rem
Blood Forming Organs (leukemia)	28.4
Lung	22.2
Bone**	21.0 0.7
Gastrointestinal Tract	3.4
Thyroid***	13.4 0.006
Whole Body****	125.0 (accidents) 25.0 (accident-free)

*Adjusted for age distribution within the U.S. population.

**The value of 21.0 is used for high-LET isotopes.
The value of 0.7 is used for low-LET isotopes.

***A value of 13.4 is based on an average individual thyroid dose of greater than 1500 rem and is used for all thyroid doses from X-ray or γ sources. The value of 0.006 is used for internal thyroid exposures to non-penetrating radiation such as those originating from I-131 uptake.

****As explained in the text, a dose rate effectiveness factor is used for whole-body exposure from the extremely low dose rates encountered in normal transportation.

Lung. The prime sources of data on lung cancer rates are also References 5 and 8. These data do not distinguish between smokers and non-smokers and do not consider the "hot particle hypothesis"[13] which has not received widespread acceptance in the scientific community.[14,17] Mays[18] computes a value of 200 lung cancers per 10^6 person-rad for high LET radiation which is consistent with the value of 22.2 per 10^6 person-rem chosen for this assessment.

Bone. The principle data source used for bone cancer fatality risk values was Reference 5, which used age group adjustment factors to derive a value of 6.9 bone cancer fatalities per 10^6 person-rem based on information in Reference 8. More recent information[18,19] suggests that this value may be low by as much as a factor of 3 for long-lived bone-seeking alpha emitters such as Pu-239 and Am-241, and high by as much as a factor of 10 for shorter half-life nuclides emitting low LET radiation. Thus, two values are included, and bone seekers are segregated into high LET/long half-life or low LET/short half-life groups.

Gastrointestinal Tract. The data base for radiation-induced cancers of the GI tract derives principally from high dose rate X-ray exposures. Current animal experimentation at varying doses and dose rates has failed to show pathological changes in these tissues.[20] There does, however, appear to be significant variation of radiation damage in the various portions of the GI tract.[5,8,21] The value of 3.4 cancer fatalities per 10^6 person-rem was chosen based on Reference 5. This does not account for the variable sensitivity of the different segments of the GI tract.

Thyroid. The degree of susceptibility of the thyroid to carcinogenesis is not universally agreed upon. In terms of cancer incidence (not fatalities), values ranging from 0.064 per 10^6 person-rem[5] to 230 per 10^6 person-rem can be obtained.[5,22-25] The two most significant factors in this wide variation are age at irradiation, and whether the radiation source was external (as in patients treated for head and neck disorders with X rays) or internal (as in persons receiving doses from I-131 in fallout). For the quantification of fatalities from thyroid cancers, this assessment uses a 10 percent fatality rate as suggested in Reference 5 (p. 9.26), and uses the value of 134 thyroid cancers per 10^6 person-rem for external irradiation (consistent with References 5 and 22), and 0.06 thyroid cancers per 10^6 person-rem for internal irradiation.[5] This choice of values is consistent with Reference 22 and is an intermediate value among those found in the literature.

External Whole Body Irradiation. Using a linear dose response model, external whole body exposure has been estimated to result in 125 fatal malignancies (including 25 leukemias) at high dose rates (above about 10 rads/min), and 25 fatal malignancies (including 5 leukemias) at lower dose rates (less than 0.01 rad/min)[18] per 10^6 person-rem. If a sigmoid dose response relationship is assumed for low LET radiation, the values for fatal malignancies become 0.5 and 0.02 respectively.[18] For the purposes of this study, the linear model is assumed, so that 125 fatal malignancies per 10^6 person-rem whole-body exposure is used in the case of accidents where dose and dose rates can be large,and 25 fatal malignancies per 10^6 person-rem whole-body exposure is used in the case of radiation exposure from accidents where dose and dose rates are small, and also for accident-free transport of radioactive material where the individual doses and dose rates are extremely small.

2.2.2 Genetic Effects

Genetics is concerned with the study of heredity. Specific linear base sequences of the nucleic acids in a cell determine the activities of the cell and the characteristics of the individual. The base sequences are carried in the chromosomes and are transmitted to the next generation when the cell divides. A change in any specific linear sequence, commonly called a mutation, changes the information which is passed on.

Mutations are usually detrimental, and every individual appears to carry a "load" of defective genes which collectively tends to reduce his overall fitness to some degree. During the evolutionary past, an equilibrium between mutation rates resulting from "favorable" gene modifications and natural selection against detrimental genes has been established for each species.[21] However, concern within the radiobiology community has arisen because of laboratory work which has shown radiation to be mutagenic in lower life forms such as Drosophila (fruit flies) and various species of mice. These data have been extrapolated to dose-effect relationships in man,[8,21,26] although this extrapolation is a tenuous and possibly inaccurate procedure.

When evaluating genetic effects, the significant dose is that received by the gonads. If integrated gonadal exposures are known, estimates can be made of the number of various types of genetic effects, which might be expected to occur in all subsequent generations as a result of that exposure using statistical information similar to that used for carcinogenesis. Values for four types of genetic effects considered are shown in Table 3, assuming a doubling dose (the dose of radiation which induces the same number of mutations as arise spontaneously in one generation) of 100 rem. These values account for the variation in child-bearing probability as a function of parental age by using statistics on live births as a function of paternal age.[5]

TABLE 3

GENETIC EFFECTS RISK COEFFICIENTS[5]*

Genetic Effect	Cases (in all subsequent generations) per 10^6 Person-Rem to Gonads
Single-gene disorders	42
Multifactorial disorders	84**
Congenital disorders	6.4
Spontaneous abortions	42
Total Genetic Effects	~ 170

*Assuming a doubling dose of 100 rem.

**Upper limit of range 8.4-84

3. Radiation Exposure Pathways

To relate the health effects resulting from individual and integrated radiation exposure to an organ dose, specific radiation exposure pathways must be considered. These radiation exposure pathways include ingestion, external irradiation by radionuclides in the environs of persons, and inhalation of radionuclides. External irradiation can result from accident-free transport, from an accident involving loss of shielding from a nondispersible material, from cloudshine (dose from passing cloud), or from groundshine (dose from deposited radionuclides) following a dispersal accident.

3.1 Ingestion of Radionuclides.

Of all transported radionuclides, only isotopes of iodine, strontium, and cesium are important from an ingestion viewpoint.[5,27] The only credible means by which these radionuclides might be accidentally ingested is by consumption of foodstuffs, (milk, meat) and/or water. Since the scope of this assessment is limited to events occurring in urban areas, and since a very small fraction of foodstuffs consumed in an urban area is produced in that area (i.e., home vegetable gardens, etc.), consumption of contaminated drinking water is the only significant pathway for accidental ingestion of radionuclides released to the environment from a transportation accident in an urban area. The range of capacity of the various reservoirs associated with the New York City water system is $0.9 \times 10^9 - 144 \times 10^9$ gallons.[28] The maximum permissible concentration (MPC) in water for the radionuclides of primary interest (I-131, Sr-90, Cs-137) are 2×10^{-5} μci/ml, 10^{-6} μci/ml, and 10^{-8} μci/ml, respectively.[29] Therefore, a release of between 68 and 10,900 curies of I-131, 3.4 and 544 curies of Sr-90, or 0.034 and 5.45 curies of Cs-137 directly into reservoirs within this water system would be required to exceed their respective MPC's. A typical I-131 package shipped in 1974 contained less than 10 curies[27] so I-131 can be eliminated as an ingestion hazard by assuming that the contaminant is completely soluble and uniformly mixed in the reservoir, and by assuming concentrations of less than MPC will not make a significant radiological dose contribution to the overall environmental impact. Although Cs-137 and Sr-90 are shipped in quantities large enough to result in exceeding the MPC, under conceivable, but unlikely, circumstances, it is anticipated that if either of these radionuclides were spilled into a reservoir, action would be immediately taken to insure that a minimal amount of contaminated water would be consumed. This would minimize the radiological consequence at the expense of a potentially high socio-economic consequence.

3.2 External Radiation Exposure

External irradiation can result from an accident involving loss of shielding from a nondispersible radioactive material, from cloudshine, or from groundshine following an accident involving dispersal of radioactive material. This type of radiation exposure is assumed to be whole body, low LET, penetrating radiation. The critical organ is total bone marrow. Dose to the skin, lens of the eye, or other external doses from high LET radiation are not evaluated.

An argument similar to that presented to eliminate strontium and cesium from consideration as ingestion hazards is used to eliminate groundshine doses from consideration as external exposure hazards, particularly in an urban area. Clearly, any release of radioactive material which is of sufficient magnitude to deposit quantities of radioactive material near an accident site, and large enough to cause a groundshine hazard would result in that site being cordoned off and cleaned up, as in the case of chemical spills or oil spills, so that the dose to the general public from groundshine would be limited.

3.3 Inhalation of Radionuclides

The basic model used to describe the inhalation and eventual body transport of radionuclides is the ICRP Task Group II Lung Model,[30] shown schematically in Figure 3. The model has been used extensively and is only briefly described here.

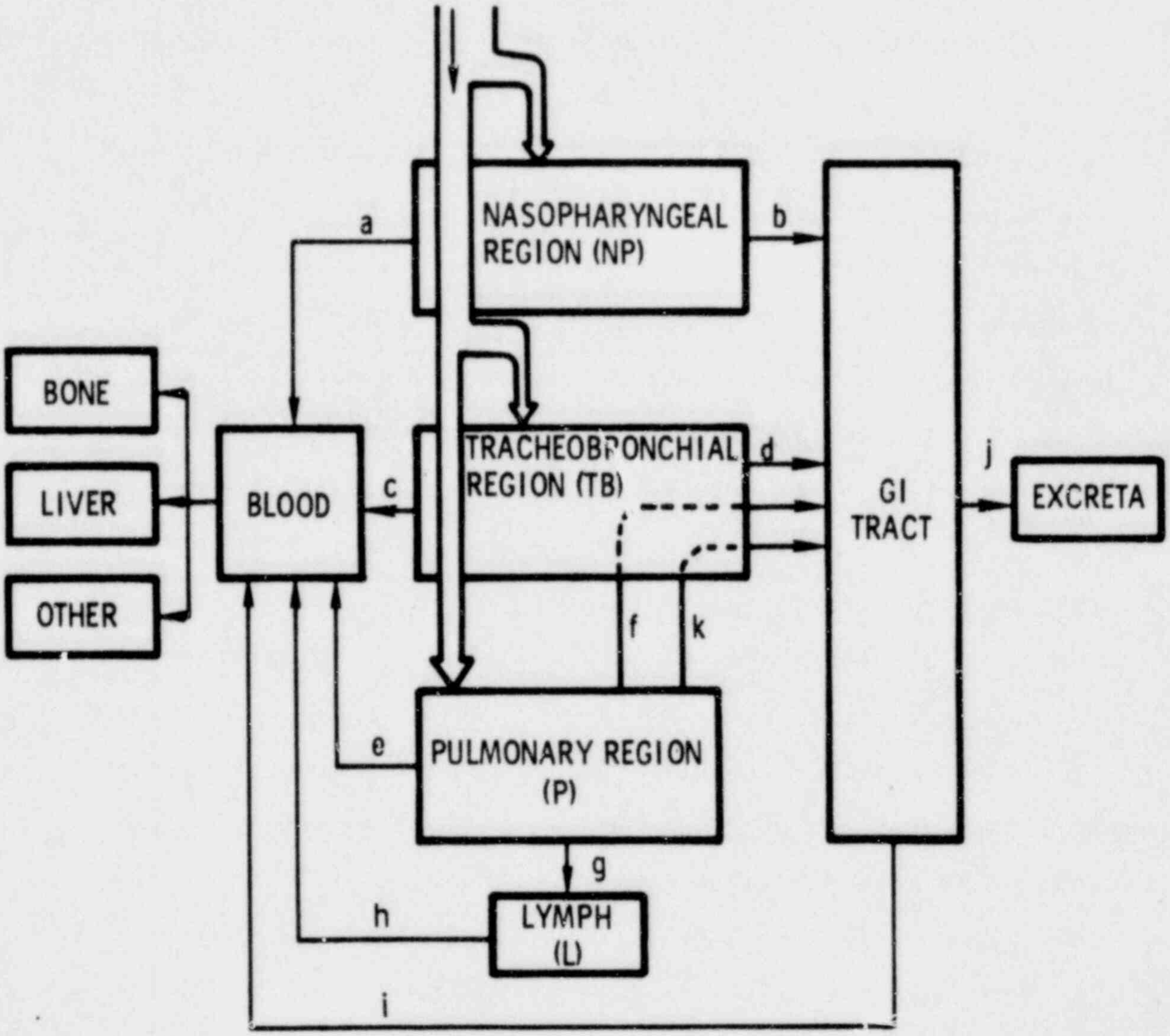

Figure 3. Biological Pathways for Inhaled Material

a. Nasopharyngeal absorption in blood
b. and (d) Muco-ciliary translocation to upper GI tract
c. Tracheobronchial absorption in blood
e. Alveolar diffusion (solubilization)
f. Short-term and (k) long-term muco-ciliary translocation of phagocytized material to tracheobronchial region
g. Absorption into lymphatic system
h. Transfer to venous system
i. Gastrointestinal absorption in blood
j. Excretion from GI tract as feces or absorption from GI tract and excretion as urine

Large particles (> 10 micrometers in equivalent aerodynamic diameter [AMAD]) are selectively deposited from inspired air in the nasopharyngeal passages. They are captured in the mucoid lining of the passages, transported by the cilia with the mucus drainage, and eventually swallowed (pathway b on Figure 3). Intermediate sized particles (1 to 10 micrometers in equivalent aerodynamic diameter) are deposited principally in the pulmonary or naso-pharyngeal region with a small fraction depositing in the tracheobronchial region. Some of the particles also become entrained in the mucoid lining and are moved upward towards the pharynx by muco-ciliary action for eventual deposition into the upper GI tract (pathway d in Figure 3). In addition, a small number of these particles are dissolved in blood (pathway c on Figure 3). Small particles (< 1 micrometer in equivalent aero-dynamic diameter) are preferentially deposited in the pulmonary region. They come in direct contact with the alveoli and are rapidly phagocytized and localized in the reticuloendothelial cells of the alveoli. The relative fractions depositing in the three zones as a function of particle size are shown on Figure 4.

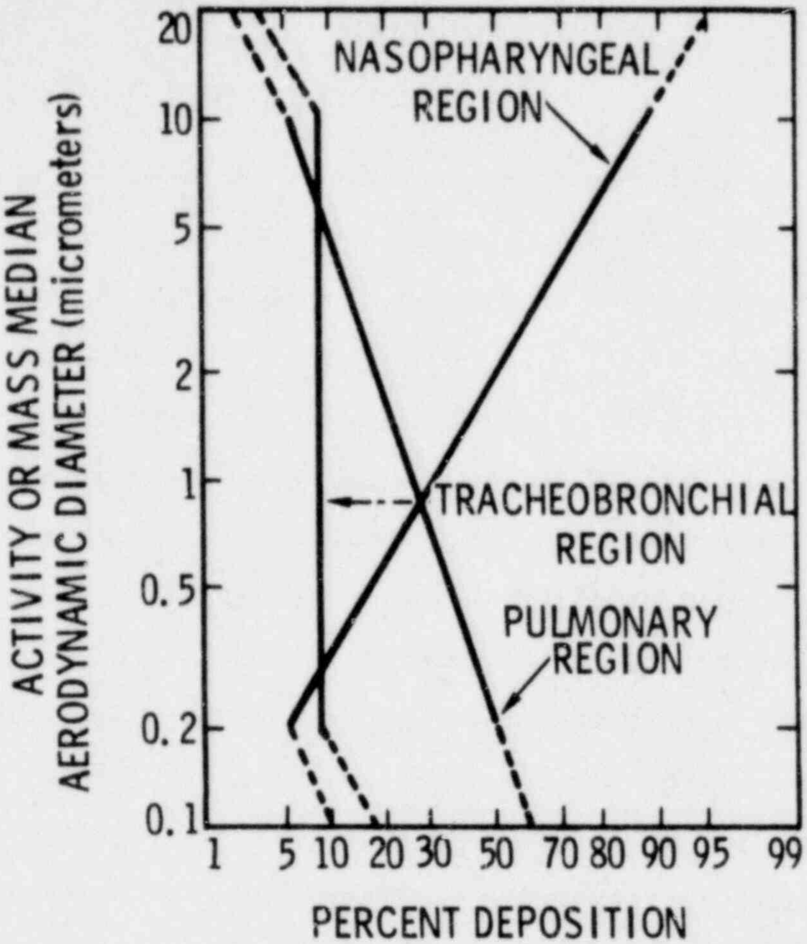

Figure 4.[5] Deposition model. The radioactive or mass fraction of an aerosol that is deposited in the nasopharyngeal, tracheobronchial, and pulmonary regions is given in relation to the activity of mass median aerodynamic diameter (AMAD) or (MMAD) of the aerosol distribution. The model is intended for use with aerosol distributions that have an AMAD or MMAD between 0.2 and 10 micrometers with geometric standard deviations of less than 4.5. Provisional deposition estimates further extending the size range are given by the broken lines. For the unusual distribution having an AMAD or MMAD greater than 20 micrometers, complete nasopharyngeal deposition can be assumed. The model does not apply to aerosols with AMADs or MMADs below 0.1 micrometer.

The question of the effect of particle size on the pulmonary solubilization rate (pathway e on Figure 3) has been investigated.[31-35] The concensus is that, for spherical particles, the dissolution rate for a chemical form of given physiological solubility varies according to particle size. Thus, the lung dose for a given lung burden would be smaller for larger particles since they would dissolve more rapidly. However, other organ doses would be correspondingly larger. This effect is included in the model by appropriately modifying the rem/curie inhaled values for each organ. Some work has been done on phagocytosis rates[36] (pathway g on Figure 3) with the general conclusion that the effect is a small one. No information is currently available on particle size effects on ciliary transport (pathways f and k on Figure 3) although those effects are also considered to be small. Thus, the significant effects of particle size which are treated explicitly in the model, are pulmonary deposition fraction and solubilization.

Depending on its chemical nature, the radionuclide may translocate after being deposited in the lung and will cause the most significant biological damage to the critical organ (or organs). The dose received by the organ or organs determines the most significant biological effects of the exposure.

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APPENDIX I

DOT Incidents in Urban Environs

(1971 - 1977)

Involved Material	Class By Use	Date of Incidents	DOT #	Mode of Transport	Location in Urban Area	Nature of Incident	Human Error
Am 241 SF	Industrial	8 Jun 73	None	Air passenger	Ramp and aircraft Detroit, MI	Water collection No contamination	Stowage
Cd 115 m & Mn 54	Industrial	3 Jan 75	5010161	Air freight	Air freight warehouse, Boston, MA	Crushed box	Stowage
C-14 Bicarbonate H-3	Industrial-research	22 Dec 75	6010005	Air passenger	Cargo Bldg. #61 JFK NY	Dropped in handling external puncture crushed by tractor	Stowage
C-14	Research	6 Dec 75	5120346	Air passenger	Gate 10 at airport Minneapolis-St. Paul, MN	Crushed by vehicle	Stowage
C-14	Research	26 Sep 75	5090783	Truck-freight forwarder	Street in front of hospital Torrence, CA	Run over by auto	Stowage
C-14	Research	21 Jun 75	5060967	Air freight	D-Concourse ORD Minneapolis-St. Paul, MN	Blown off tug by blast from passing aircraft	Stowage
C-14	Research or Industrial	5 May 75	None-see file	Mail U. S.	Post Office Baltimore, MD	Damaged in handling	Handling
C-14, H-3	Industrial-research	1 Aug 74	4080698	Air passenger	Air freight facility - Boston, MA	Run over by fork lift	Stowage
C-14	Research	15 Aug 73	None	Air passenger	Foreign cargo area - Chicago, IL	Container damaged both ends open	Handling
Cs-137 (SF) (2-sealed sources)	Industrial	11 May 77	7051203	Air freight	Air freight term. warehouse, JFK New York Jamaica	Dropped in handling external puncture	Handling
Cs-137	Industrial	27 Feb 76	6030302	Truck	Freight terminal Minneapolis, MN	External puncture	Handling
Cs, Ra waste	Industrial	19 Jan 73	None	Truck	Freight Dock Nashville, TN	Dropped in handling	Handling

Involved Material	Class By Use	Date of Incidents	DOT #	Mode of Transport	Location in Urban Area	Nature of Incident	Human Error
Cr-51	Research	9 Feb 76	6020670	Air passenger	Air freight facility, San Antonio, TX	Damaged by other freight	Stowage
Cr-51	Research	2 Dec 75	5120504	Air passenger	Air freight facility, Chicago, IL	Dropped in handling	Handling
Cr-51	Research	13 May 75	5050732	Air passenger	Freight facility Boston, MA	Spill handled by NEN	Unknown
Cr-51, Am-198 I-125, Mo-99	Industrial	9 Mar 74	4030232	Air passenger	Aircraft aft bulk cargo bin Minneapolis, MN	Damaged by other freight, prior water damage	Stowage
Cr-51	Research	20 Apr 73	None	Air passenger	Freight area Washington, DC	Dropped in handling	Handling
Co-60 and Cs-137 LSA	F.C. waste	4 Oct 76	6110102	Truck	Freeway - I95 at NC rte 46, Gaston, NC	Top of box opened during transport	Packaging
Co-57 flood source	Research	11 Feb 76	6030626	Truck	Clark Ave. Bridge Cleveland, OH	Box fell off trailer run over by following vehicle	Stowage
Co-57	Industrial	16 Sep 75	5100211	Air freight forwarder	Terminal Atlanta, GA	Damaged in handling	Handling
Co-60 SF	Industrial	2 Oct 74	[illegible]100433	Truck	In trailer Tulsa, OK	Fell in transit	Stowage
Co-60	Research	24 Dec 74	4080493	Truck	In trailer at terminal San Antonio, TX	Outside container cracked	Stowage
Co-60	Industrial	10 Feb 74	4020263	Truck	Freight term. Memphis, TN	Damaged by other freight - crate bashed in	Stowage
Co-60	Industrial	10 Sep 71	1160076	Truck	Industrial company, Leechburg, PA	Loose fittings valves or closures	Packaging
Co-60	Industrial	10 Jul 71	1080013	Truck	U.S. 63 city limits, Cabol, MO	Vehicle accident	Accident
Ga-67 Citrate	Industrial	29 Jan 77	7020741	Truck	Freeway, NJ turnpike between 82 and 92 Northbound	Fell out of truck	Stowage

Involved Material	Class By Use	Date of Incidents	DOT #	Mode of Transport	Location in Urban Area	Nature of Incident	Human Error
Ga-67 Citrate	Industrial	24 Nov 74	4120235	Air passenger	Terminal warehouse Boston, MA	Dropped in handling external puncture damage by other freight	Handling
I-131	Radiopharm	30 May 77	7061369	Truck	Freight term. Kansas City, MO	Package stolen	Theft
I-125	Research	5 May 77	7050465	Air freight	Air freight term. Greensboro, NC	Lack of internal padding	Packaging
I-123	Research	29 Mar 77	7040557	Air freight	Air freight term. San Francisco, CA	Run over by fork lift	Stowage
I-125	Research	25 Mar 77	70400[illegible]	Air passenger	Air freight facility Colorado Springs, CO	Failure of inner receptacles	Packaging
I-123 and Ga-67	Research	13 Dec 76	6120668	Air passenger	Air freight dept. Indianapolis, IN	Shipment picked up fraudulently	Theft
I-125, C-14, H-3	Research	13 Nov 76	6110776	Air passenger	Indianapolis, IN	Air freight never arrived	Lost
I-123	Research	22 Jun 76	6070001	Air passenger	TWA Cargo Bldg. 81, JFK, NY	Dropped in handling	Handling
I-125	Research	27 May 76	6050001	Air passenger	Air freight fac. #8, JFK, NY	Failure of inner receptacles	Packaging
I-131 and I-125	Industrial-research	21 May 75	5070001	Air passenger	SAS Cargo Dept. Cargo Bldg. #1 Los Angeles, CA	Dropped in handling	Handling
I-131	Industrial or Radiopharm	6 May 75	5050730	Air passenger	Ramp in baggage cart St. Louis, MO	Dropped in handling	Handling
I-125	Industrial or Research	21 Feb 75	5030034	Air passenger	Cargo Terminal San Francisco, CA	Dropped in handling	Handling
I-131	Radiopharm	6 Feb 75	5020420	Air passenger	On aircraft at landing Honol[illegible], HI	Wet and damaged	Stowage
I-131	Research	17 Jan 75	5010542	Air passenger	Ramp behind air freight warehouse Seattle-Tacoma, WA	Outer packing damaged	Handling
I-125, Cr-51, I-131, Cd. Au, C1-36	Industrial or Research	10 Jan 75	5010909	Truck	Tremont St. L. Eastbound and New Dudley St. at N. Dudley Square Roxberry, MA	Traffic accident	Accident

Involved Material	Class By Use	Date of Incidents	DOT #	Mode of Transport	Location in Urban Area	Nature of Incident	Human Error
I-131	Industrial	7 Jan 75	5010253	Air freight	Air freight term. Washington, D.C.	Water damage, body or side failure	Handling
I-125	Research	31 Aug 74	4090307	Air passenger	Freight warehouse Minneapolis, MN	Run over by forklift	Stowage
I-125	Industrial	20 Aug 74	4090003	Air passenger	Air freight ware-house, Chicago, IL	Damaged container put in trash	Disposal
I-131	Industrial	9 Aug 74	4080630	Truck	Freight facility Great Falls, MT	Damaged by other freight	Stowage
I-131	Industrial	17 Jul 74	4070805	Air passenger	Cargo Bldg. 81 (TWA) JFK, NY	Dropped in handling	Handling
I-125	Industrial	4 Jul 74	4070349	Air passenger	Tractor tug pulling full baggage cart San Francisco, CA	Jet blast knocked box off, then tractor crushed.	Stowage
I-123	Research	16 Jun 74	4080497	Air passenger	Air freight term. Boston, MA	Body or side failure	Packaging
I-125	Industrial	18 Apr 74	4050132	Air passenger	Air freight term. fork lift, JFK, NY	Outer carton damage	Handling
I-123, Tc99M	Radiopharm	11 Apr 74	4040404	Air passenger	DC-8-61 Air craft Dallas-Ft. Worth, TX	Dropped in handling, external puncture	Handling
I-125	Research	6 Aug 73	3080191	Air passenger	At aircraft JFK, NY	Fell from cart, subsequently crushed	Stowage
I-131	Research	26 Jul 73	3100274	Air passenger	Cargo area, Dallas Love Field, TX	Bottom failure	Packaging
I-131	Research	24 May 73	5020002	Air passenger	Air freight term. Los Angeles, CA	Dropped in handling external puncture	Handling
I-131	Research	22 Jun 72	None	Air passenger	Aircraft cargo bin, Houston, TX	External puncture	Handling
Ir-192	Industrial	18 Dec 74	4120638	Air passenger	Air freight term. Baton Rouge, LA	Defective valves fittings or closures	Packaging
Ir-192 SF	Industrial	5 Sep 74	4100206	Air passenger	In aircraft Syracuse, NY	Bottom failure, corrosion or rust	Packaging
Ir-192	Industrial	27 Aug 74	4090359	Air passenger	Airport freight Newark, NJ	Probable container defect	Packaging
Ir-192	Industrial	8 Apr 74	4040403	Air passenger	In transit Baton Rouge, LA	Improper packaging	Packaging
Ir-192	Industrial	10 Mar 74	4030399	Truck	Route 422 at 645 Myerstown, PA	Vehicle accident, no damage to shipment	Accident

Involved Material	Class By Use	Date of Incidents	DOT #	Mode of Transport	Location in Urban Area	Nature of Incident	Human Error
Ir-192	Industrial	4 Sep 73	None	Air passenger	Freight area Dallas Love Field, TX	Dropped in handling	Handling
Ir-192	Industrial	28 Mar 73	None	Air passenger	727 aircraft at airport Washington, DC	Dropped in handling	Handling
Ir-192	Industrial	17 Apr 72	2040228	Air passenger	Airlines station Duluth, MN	Top cover of outer box open one end.	Packaging
Ir-192	Radiopharm	7 Jan 72	2010137	Air passenger	On aircraft Washington, DC	Loose fittings, valves, or closures.	Packaging
Kr-85	Unknown	18 May 76	6050863	Truck	Freight term. Louisville, KY	Water damage	Stowage
Mo-99 (N.O.S.)	Research	25 Apr 77	7050640	Air passenger	Cargo Terminal New Orleans, LA	Defective fittings valves or closures	Packaging
Mo-99	Research	18 Sep 75	5090739	Air passenger	On aircraft at terminal, Salt Lake City, UT	Water damage	Stowage
Mo-99	Research	23 Feb 75	5030250	Air passenger	Air freight term. Denver, CO	Water damage	Stowage
Mo-99, Tc 99m generator	Research	28 Jun 74	4070266	Air passenger	En route to LaGuardia NY on arrival in Dayton, OH	Fell off truck checked for damage	Stowage
Mo-99	Industrial	16 Feb 74	4030098	Air freight	Airport ramp spot #5 Tuxedo, NY	Bottom, body and side failure	Packaging
Mo-99 - Tc99m	Research	8 Jan 72	2020138	Air passenger	Passenger term. aircraft apron JFK, NY	Dropped in handling	Handling
Mo-99	Research	31 Dec 71	2010124	Air passenger	Aircraft at airport and en route Atlanta, GA	Spillage but <u>no</u> contamination	None
Tc-99m	Research	27 Feb 75	5030413	Air passenger	Planeside and freight terminal Pittsburgh, PA	Water damage, damaged by other freight. Failure of inner receptacle.	Stowage
Tc-99m	Research	2 Jan 75	5010959	Air passenger	Air freight term. Chicago, IL	Loose fittings, valves or closures	Packaging
Tc-99 spent generator	Research	8 Oct 74	4100585	Truck	In trailer Atlanta, GA	External puncture body or side failure	Stowage

Involved Material	Class By Use	Date of Incidents	DOT #	Mode of Transport	Location in Urban Area	Nature of Incident	Human Error
Tc-99	Industrial	1 Aug 73	N3080034	Air passenger	Freight area JFK, NY	Outer container open	Packaging
P-32	Industrial-research	15 Aug 73	N3090017	Air passenger	Freight area Denver, CO	Dropped in handling cart ran over end of carton	Stowage
Plutonium samples	Industrial	6 Dec 75	5120517	Truck	I70 at Ind. 227 Richmond, IN	Fell out of moving trailer	Stowage
Po-210-ionizing annozzle (NOS)	Industrial	13 Jan 77	7020163	Air freight forwarder	Air cargo term. DFW, TX	Dropped in handling	Handling
Ra-226	Moisture Density Nuclear Testing Equip-Industrial	8 Mar 76	6030462	Truck	On truck Beckley, W. Va. or Research Pk., NC	Damage by other freight	Stowage
Ra-226	Research	24 Mar 75	5040001	Air passenger	NW Gate D8 Ramp-on craft Chicago, IL	Outside container crushed	Stowage
Radium eqpt.	Industrial	4 Sep 74	4090528	Air passenger	In aircraft at ramp gate, Minneapolis, MN	Loose fittings, top closeness	Packaging
Ra-226	Industrial	30 May 73	None	Truck	Dock, freight terminal Memphis, TN	Damaged crate	Handling
Ru-106	Industrial	27 Feb 76	6030304	Air freight	SAS Cargo Bldg. 263-JFK, NY	Carton crushed-cause unknown	Stowage
Se-75, NOS	Research	4 Mar 77	7030383	Air passenger	Passenger aircraft baggage cart Montreal, CN	No actual contamination	Unknown
Se-75	Research	3 Jul 73	3070241	Air passenger	On DC9 Aircraft New Orleans, LA	Dropped in handling	Handling
Sr 85, Y6169	Research	29 Jul 72	None	Air passenger	Aircraft and air freight, Denver, CO	Damaged by other freight	Stowage
Thoric Oxide	Industrial	5-6 Jul 77	7070342	Truck	Dock facility Port Seatrain LTL Facility Weehawken, NJ	Damaged by other freight	Stowage
Natural thorium 23% as ThO_2	Industrial	21 Feb 77	7030876	Truck	Freight terminal Portland, OR	No actual contamination side of containers crushed by other freight	Stowage
Thorium	Government	11 Oct 75	5100990	Truck	Freight terminal on truck, Atlanta, GA	Improperly loaded	Stowage

Involved Material	Class By Use	Date of Incidents	DOT #	Mode of Transport	Location in Urban Area	Nature of Incident	Human Error
Thorium Nitrate	Industrial	4 Sep 74	4090323	Truck	Freight dock Kansas City, MO	Powder spill from drum	Packaging
H-3	Industrial or Research	9 Oct 76	6100372	Air freight forwarded	Cargo Bldg. Pittsburgh, PA	Damaged by other freight	Stowage
H-3	Industrial-research	24 Feb 76	6030381	Truck	Freight term. Omaha, NE	Loose fittings, valves or closures	Packaging
H-3	Industrial	27 Jan 76	6020328	Truck	UPS facility Albuquerque, NM	Loose fittings, valves or closures. Failure of inner receptacles	Packaging
H-3	Industrial (?)	5 Sep 75	5090740	Air passenger	Air freight term. Salt Lake City, UT	Water damage	Stowage
H-3, C-14, S-35, Cr-51, and I-125	Research	15 Aug 75	5080980	Truck	Freeway south-bound on NY Thruway, Pelham, NY	Boxes fell out and crushed by following traffic	Stowage
H-3	Research	1 Mar 74	4030170	Air passenger	Vehicular roadway in airport area, Washington, DC	Rolled off truck	Stowage
H-3	Research	30 Jan 74	4020394	Air passenger	Freight parts room Amarillo, TX	Top crimped, metal lid open	Packaging
H-3	Research	28 Jun 73	3070270	Air passenger	United Air Freight Hangar, Cleveland, OH	Dropped in handling bottom failure, external puncture	Handling
H-3	Research	20 Jul 72	2070380	Air passenger	Aircraft cargo bin Washington, DC	Box opened - no damage	Packaging
H-3	Industrial (?)	29 Apr 72	2050044	Air passenger	Air freight facility, Chicago, IL	Crushed by forklift	Handling
Uranium, natural as U_3O_8 LSA	(1) F.C.	23 Jul 77	7080475	Rail	Rail yard Pueblo, CO	Dropped in handling	Handling
	(2) F.C.	2 Jun 77	7060416	Truck	Freeway Denver, CO	Defective fitting or valves	Packaging
Uranyl Nitrate	Radiopharm	4 Feb 77	7030125	Truck	UPS package sorting fac. Edison, NJ	Failure of inner receptacle	Packaging
Uranium as U_3O_8	F.C.	31 Jan 77	7020934	Handling (Exxon Nuc. Co., Inc.)	Dockside warehouse Port Covington, Baltimore, MD	(Unknown)	Handling
Uranium concentrates LSA	Industrial	11 Jan 77	7020179	Truck	Urban Metropolis, IL	External puncture	Unknown

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Involved Material	Class By Use	Date of Incidents	DOT #	Mode of Transport	Location in Urban Area	Nature of Incident	Human Error
Depleted Uranium U F_4	Industrial	28 Sep 75	5090817	Truck	Freight term. Johnson City, TN	External puncture	Handling
U235 fissile	Industrial-research	13 Feb 75	5020420	Truck	6th St. at Almon St. Moscow, ID	Dropped off truck	Stowage
Uranium ore	Industrial	5 Feb 75	None	Truck	Freight terminal St. Louis, MO	Drum ruptured	Packaging
Ore samples	Industrial	15 Aug 74	4090721	Truck	Freight dock Phoenix, AZ	Loose fittings valves or closures	Packaging
Uranium oxide yellow cake	Industrial	22 Dec 73	4020081	Truck	On trailer at freight terminal Oklahoma City, OK	Body or side failure corrosion or rust	Packaging
Nat'l Uranium Conc.	F.C.	17 Nov 73	3120045	Truck	Dock and trailer Denver, CO	External puncture	Handling
Uranium concentrate, LSA	Industrial	5 Dec 72	2120186	Truck	Truck terminal Denver, CO	Weld failure	Packaging
Enriched uranium, fissile	Industrial	27 Mar 72	2040116	Truck	Freight facility Bristol, VA	External puncture	Handling
Xe 133	Research	3 Feb 76	6030303	Air passenger	Air cargo term. Knoxville, TN	Failure of inner receptacle	Packaging
Xe 133	Research	2 May 75	5050185	Air freight	Fed. Exp. Hub sorting facility Memphis, TN	Damaged by other freight	Stowage
Xe 133	Research	22 Dec 72	2120341	Air passenger	On plane at airport Newark, NJ	Damaged by other freight	Stowage
Yterbium 169	Industrial	28 Aug 74	4090112	Air passenger	LAX Aircraft Ramp, Gate Conveyor Belt Los Angeles, CA	Fell off belt, dented	Handling
Radionuclide	Industrial	6 Jul 77	7070949	Truck	Freight terminal Brisbane, CA	Container shield failure	Packaging
Radioactive Mat'l (NOS)	Unknown	23 Jun 77	7061277	Air freight	Freight term. Denver, CO	Box slightly wet on bottom	Stowage
Radioactive Mat'l	Industrial	10 Feb 77	7030123	Truck	Truck terminal Ruby, SC	Trailer contamination	Unknown
Radioactive pharmaceutical	Research	4 Oct 76	6100469	Truck	US41 between N. Chicago & Highland Park, IL	Dropped on roadway from truck	Stowage

Involved Material	Class By Use	Date of Incidents	DOT #	Mode of Transport	Location in Urban Area	Nature of Incident	Human Error
Radioactive Material	Industrial	24 Aug 76 and 18 Aug 76	6110054	Truck	Industrial Plant Pleasanton, CA	Dropped in handling	Handling
Unknown	Unknown	16 Aug 76	6090692	Truck	Truck terminal Seneca, IL	Spillage on deck	Packaging
Radioactive Material	Research	26 Jul 76	6080344	Air freight	Freight facility ramp, Boston, MA	Run over by forklift	Stowage
Radioactive biological samples	Research	3 Mar 76	6030339	Truck	Truck terminal Peoria, IL	Loose fittings, valves or closures	Packaging
Electronic radio-active equipment	Industrial	27 Feb 76	6030028	Truck	Freight terminal St. Paul, MN	External puncture	Handling
Radioactive Mat'l, Isotopes Unknown	Unknown	3 Jan 76	6010636	Truck	Canal St. near Broadway, New York City, NY	Theft	Theft
Unknown	Industrial	16 Aug 75	5080982	Truck	In city on truck Pittsburgh, PA	Box fell - improper loading	Stowage
Unknown	Industrial	16 Aug 75	5080981	Truck	In city on truck Pittsburgh, PA	Two boxes fell improper loading	Stowage
Radioactive source charger	Industrial	17 Dec 71	5010288(3?)	Truck	Freight terminal Lebanon, PA	Improper loading	Stowage
Unknown	Research	1 Aug 74	4080265	Air passenger	On aircraft El Paso, TX	Box wet - damage cause unknown	Handling
Radioactive Material	Industrial	11 May 73	None	Truck	Freight dock Commerce City, CO	Defective or loose fittings, valves or closures	Packaging
Static eliminators	Industrial	10 Sep 71	1110102	Truck	Truck terminal and dock, Anderson SC	Failure of inner receptacles	Packaging
Spent fuel	F. C.	4 Jul 76	6070402	Truck (Open road)	At truck stop Rock Springs, WY	Coolant water leak	Packaging
Radioactive Mat'ls, fissile	Industrial	14 Nov 72	3010116	Truck	Freight terminal Orange, CT	Damaged by other freight, loose fittings, etc.	Stowage Packaging
RAM, fissile	Industrial	31 Oct 72	2120264	Truck	Freight terminal New Haven, CT	Damaged by other freight	Stowage
Tissue swipes of radioactive Mat'l	Waste	20 Jul 77	7080213	Truck	Freight terminal Springfield, MO	Damaged by other freight	Stowage

Involved Material	Class By Use	Date of Incidents	DOT #	Mode of Transport	Location in Urban Area	Nature of Incident	Human Error
Waste Material (most recent shipment in vehicle)	F.C. waste	9 Jun 77	7061103	Truck	Freight terminal Seneca, IL	Residual contamination on trailer	Packaging
Waste Material	F.C. waste	9 Jun 77	7061102	Truck	Freight terminal Seneca, IL	Residual on trailer	Packaging
Waste Material	F.C. waste	9 Jun 77	7061101	Truck	Freight terminal Seneca, IL	Residual on trailer	Packaging
Radioactive waste, LSA	F.C. waste	9 Feb 77	7030122	Truck	Truck terminal Barnwell, SC	Trailer contamination	Packaging
Radioactive waste, LSA	F.C.	10 Aug 76	6090620	Truck	Truck terminal Joplin, MO	Spillage on trailer	Packaging
Radioactive waste, LSA	Industrial	2 Jun 76	6090619	Truck	Truck terminal Richmond, KY	Spillage on trailer deck	Packaging
Radioactive waste	Government	28 Apr 76	6050215	Truck	Freight terminal Atlanta, GA	Improper handling	Handling
Radioactive waste, LSA	F.C.	18 Aug 75	5081017	Truck	Truck terminal Seneca, IL	Body or side failure	Packaging
Worthless Radioactive waste material	Radiopharm	1 Jul 75	5070564	Truck	Freight terminal Columbia, SC	Loose fittings, valves or closures	Packaging
Nuclear waste Thorium Fluoride	Industrial	3 Jun 75	5060472	Truck	Freight terminal Cincinnati, OH	Loose or defective valves, fittings, or closures	Packaging
Radioactive waste, LSA	F.C.-nuclear submarines	7 Aug 74	4080679	Truck	Hwy. 775 and 6th St. exit Canton, OH	Dropped in handling	Handling
Radioactive waste	Radiopharm	25 Jun 74	4060680	Truck	On truck at terminal Winston-Salem, NC	Drum failure metal fatigue	Packaging
Radioactive Mat'l, LSA	Industrial	3 Apr 74	4040129	Rail	Rail yard Hamlet, NC	Train derailed	Accident
Radioactive Material, LSA	Industrial	24 Sep 73	3100029	Truck	Truck at dock Miamisburg, OH	Corrosion or rust	Packaging
Radioactive waste	F.C.	18 Jul 72	None	Truck	Truck terminal Joplin, MO	Contamination on trailer	Packaging
Contamination	F.C.	15 Mar 72	2030227	Truck	Truck terminal Idaho Falls, ID	Residual contamination	Packaging

APPENDIX J

NRC Incidents in Urban Environs (1975)

INVOLVED MATERIAL	CLASS BY USE	DATE OF INCIDENTS	MODE OF TRANSPORT	LOCATION IN URBAN AREA	NATURE OF INCIDENT	HUMAN ERROR
C-14	Radiopharm	2 Dec 75	Air passenger	Airport Los Angeles, CA	Lost source	NONE
Cs-137 (sealed source)	Industrial	-	Auto	City street Linden, NJ	Theft	NONE
H-3	Radiopharm	-	Auto	City street Bridgeport, CO	Theft	NONE
H-3	Radiopharm	-	Air freight	JFK Airport, NY	Mishandling	HANDLING
H-3, S-35, C14, I-125, Cr-51	Radiopharm	-	Truck	New York Thruway Bronx, NY	Accident	NONE
H-3	Radiopharm	17 Dec 75	Air passenger	Airport Anchorage, AL	Accident	NONE
H-3	Research	9 Sep 75	Air freight	Fremont, MI	Lost source	NONE
I compounds	Radiopharm	11 Mar 75	Air freight	O'Hare Internat'l Chicago, IL	Crushed and leaking package	STOWAGE
I-125	Radiopharm	-	Truck	City street Paramus, NJ	Theft	NONE
I-125	Radiopharm	23 Jul 75	Unknown	Edmonton, Canada	Leakage	PACKAGING
I-131	Radiopharm	-	Truck	Ladysmith, VA	Lost source	NONE
I-131	Radiopharm	10 Feb 75	Air freight	O'Hare Internat'l Chicago, IL	Lost source	NONE
Ir-192 (sealed source)	Industrial	-	Air freight	Philadelphia Internat'l Airport Philadelphia, PA	Mishandling	HANDLING

INVOLVED MATERIAL	CLASS BY USE	DATE OF INCIDENTS	MODE OF TRANSPORT	LOCATION IN URBAN AREA	NATURE OF INCIDENT	HUMAN ERROR
Ir-192 (sealed source)	Industrial	-	Truck	City street Philadelphia, PA	Theft	NONE
Ir-192 (sealed source)	Industrial	18 Mar 75	Air freight	Mare Island Naval Shipyard Vallejo, CA	High dose rate for package due to improper instrument	PROCEDURAL
Mo-99	Radiopharm	8 Jul 75	Air freight	Air freight term. O'Hare, Chicago, IL	Crushed shipment	STOWAGE
Pu waste	Industrial	29 Jan 75	Truck (Tri State)	Beatty, NV	Improperly fasterned lid	PACKAGING
Th compounds	Industrial-research	-	Truck	BAPL, West Mifflin, PA	Mislabeling and no DOT labels	LABELING
Not Specified	Radiopharm	27 Apr 75	Air freight	Airport Detroit, MI	Leakage	NONE

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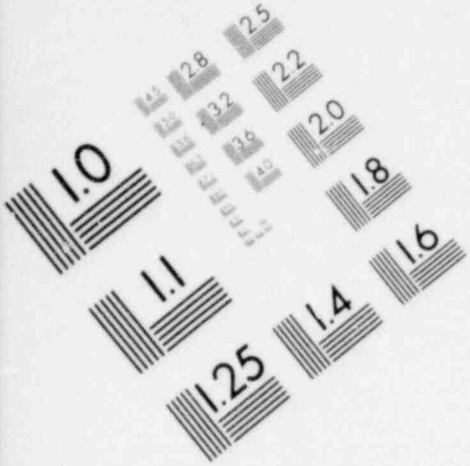

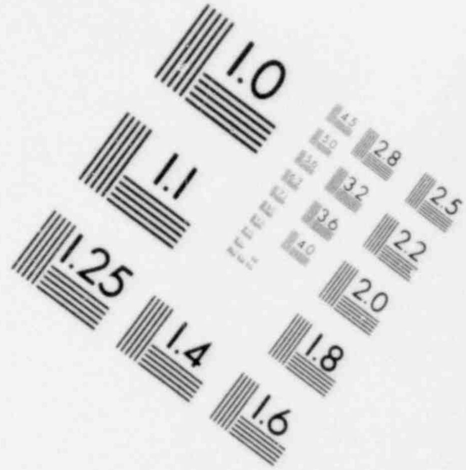

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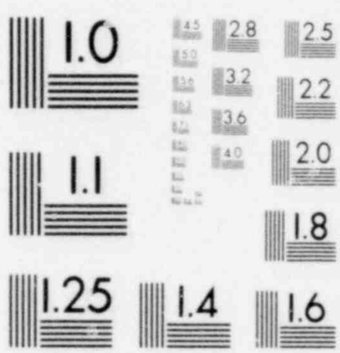

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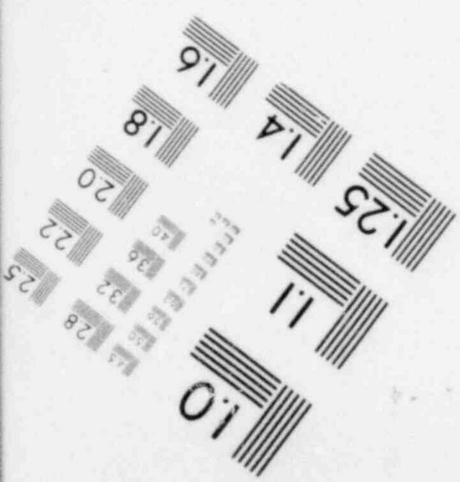

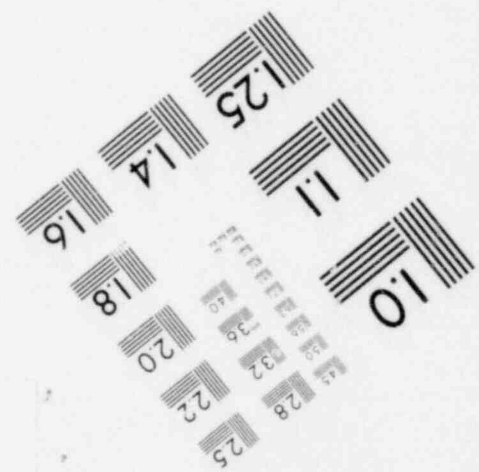

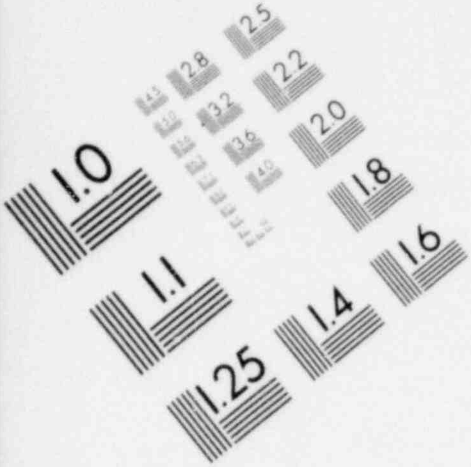

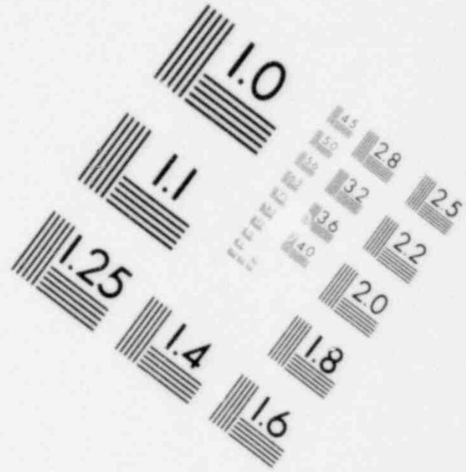

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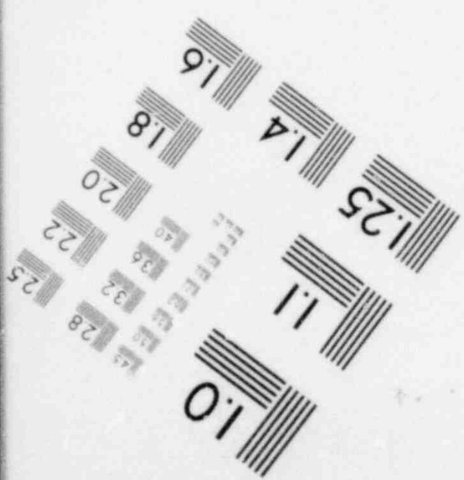

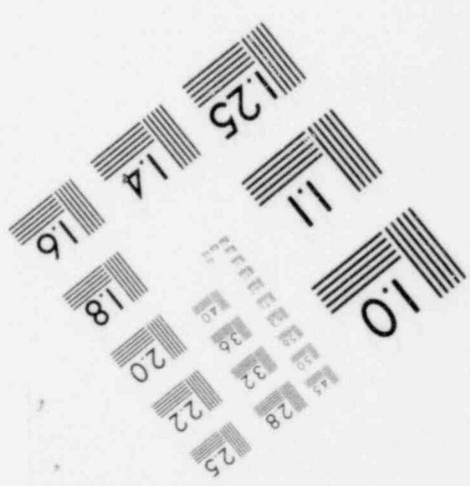

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