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**DOSE-ESTIMATION STUDIES RELATED TO
PROPOSED CONSTRUCTION OF AN
ATLANTIC-PACIFIC INTEROCEANIC CANAL
WITH NUCLEAR EXPLOSIVES: PHASE III**

Stephen V. Kays
Paul S. Rohwer

OAK RIDGE NATIONAL LABORATORY

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HEALTH PHYSICS DIVISION

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Stephen V. Kaye

and

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DECEMBER 1970

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DOSE-ESTIMATION STUDIES RELATED TO PROPOSED CONSTRUCTION OF
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WITH NUCLEAR EXPLOSIVES: PHASE III

Stephen V. Kaye and Paul S. Rohwer

ABSTRACT

This document is the final report covering contributions of the Health Physics Division of Oak Ridge National Laboratory (ORNL) to the Bioenvironmental Radiological Safety-Feasibility Study of a sea-level canal excavated with nuclear explosives. Potential doses to indigenous populations along Route 17 in eastern Panama and Route 25 in northwestern Colombia were estimated for a combination of hypothetical exposures to radiation. The studies attempted to determine when it might be appropriate for the evacuated populations to reenter areas adjacent to the two routes. The only modes of exposure considered were external exposure to a contaminated land surface and internal exposure from the ingestion of four types of contaminated foods and beverages. Parameters in the internal dose models were adjusted to differentiate five age groups within each of four indigenous populations and nine reference organs. These populations were further differentiated on the basis of diet and estimates of time- and age-dependent concentrations of radioactivity in dietary items. Intake functions (μCi ingested per day) for internal dose estimates were average values for watersheds with the highest initial areal concentration of fallout along each route, whereas external doses were computed for 13 locations (towns and villages) in watersheds of the exclusion zone of Route 17 only. Estimates of potential external doses were based on 170 radionuclides; only 31 radionuclides were considered in detail for the estimation of potential internal doses, with an approximate estimate of total dose from the radionuclides not included in the list of 31.

Estimates of potential total doses (internal dose from ingestion + external dose from land surface) were assessed in terms of radiation safety criteria recommended for members of the public by recognized authorities. The basic criteria were: annual dose

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limit for the total body of 0.17 rem/year and a genetic dose limit of 5 rems/30 years. Assessments based on somatic doses suggest reentry may be appropriate 8 to 10 years after the last detonation. Children less than 5 years of age at the time of reentry may be the critical age group among the age groups for which doses were estimated. Within this age group, no single ethnic group emerged as the most critical. Assessments based on genetic dose appear to be less limiting, suggesting that reentry may be possible within months following the last detonation. These assessments are based on comparisons with the total doses allowed under the radiation safety criteria. In actual practice, however, some apportionment of these criteria might be likely. Such an apportionment should be undertaken by the countries involved (Panama and Colombia).

1.0 INTRODUCTION

1.1 Isthmain Canal Plans

The Atlantic-Pacific Interoceanic Canal Study Commission (APICSC) is sponsoring studies of the engineering, economic, and safety feasibility of excavating a sea-level canal through the Central American isthmus. The APICSC study includes analysis of constructing sea-level canals through the Darien region of Panama (Route 17) and through northwest Colombia (Route 25) using a combination of nuclear and conventional excavation.^{1.1}

1.2 Nuclear Excavation Concept

Nuclear excavation of a canal would be accomplished by detonating rows of buried nuclear charges. These charges would break and throw large quantities of rock and earth out of the excavation in one process, eliminating need for the conventional earthmoving, and possibly resulting in significant savings in cost.^{1.2} A row of nuclear charges, each meeting certain yield limitations and operational requirements, would be detonated in a "first pass" series of detonations for each proposed route. Later, these initial excavations would be connected to form a continuous ditch by a series of "second pass" detonations. The last phase of construction would involve opening both ends by conventional excavation and dredging. Acceptable days for nuclear detonation would be determined on the basis of meteorological observations and predictions of radioactive fallout, and areas likely to be

affected by fallout would be evacuated before construction and for some time thereafter. Nuclear excavation would be carried out in such a way as to minimize any potential exposures of people to radioactivity released as a result of the nuclear detonations.

1.3 APICSC Investigations

The APICSC asked the U.S. Atomic Energy Commission (AEC) for assistance in determining the engineering feasibility of the proposed project, including safety feasibility, and AEC's Nevada Operations Office was assigned responsibility for carrying it out. Studies related to safety feasibility (i.e., airblast and seismic effects) were made by various contractor organizations. Airblast effects, seismic effects, fallout predictions, and radiological safety assessment are major areas of concern which were assigned to various prime contractors. Battelle Memorial Institute's Columbus Laboratories (BCL), one of the AEC's prime contractors engaged in this feasibility study, was given responsibility for managing the bioenvironmental studies required to evaluate radiological safety.

1.4 BCL Bioenvironmental Feasibility Study

The major objective of Battelle's work relates to determining if the nuclear excavation plan for construction of a sea-level canal can be carried out safely on the basis of a comparison of predicted radiation doses with established radiation safety standards.^{1.3} As overall technical manager of the Bioenvironmental Feasibility Study, BCL subcontracted specific aspects of the

study such as: human ecology, terrestrial ecology, aquatic ecology, marine ecology, dose estimation, hydrology, etc. Data evaluation and environmental modeling of radionuclide movement through pathways leading to man was done by BCL. The output of BCL's pathway models was the input to ORNL's dose estimation codes. Therefore, the inputs used for estimating radiation doses reflected the efforts of all the other subcontractors and BCL. Most subcontractors conducted on-site research in Panama and/or Colombia to gather data pertaining to their areas of responsibility.

1.5 ORNL Dose Estimation Study

Three major objectives of the ORNL dose estimation study were: (1) estimation of potential radiation doses to humans, (2) comparison of estimated potential doses with existing standards and guides, and (3) formulation of recommendations to limit potential radiation doses to the lowest practicable levels. Input data ($\mu\text{Ci}/\text{cm}^2$ of land surface and $\mu\text{Ci}/\text{day}$ intakes) were prepared by BCL from the contributions of participating subcontractors and made available to ORNL. Additional input data on biological and physical factors required for the computations were compiled by ORNL.

The ORNL study was divided into the following phases:

Phase I	July 1, 1966 - December 31, 1966
Phase II	January 1, 1967 - June 30, 1968
Phase III	July 1, 1968 - June 30, 1970

Phase I studies were based on literature reviews and data from preliminary reconnaissance trips by other subcontractors. The ORNL Phase I Report^{1.4} dealt with (1) methods for estimating external and internal dose equivalents, for quantifying the transfer of radionuclides through critical exposure pathways, and for identifying the radionuclides likely to be critical; (2) criteria for evaluating the radiological safety of nuclear excavation; and (3) lists of radionuclides arranged according to doses resulting from external and internal exposures to unit quantities of each radionuclide. Recommendations of recognized radiation protection authorities were used to develop criteria for assessing the radiological safety of canal construction.

A continuing effort was underway throughout Phase II to develop computer codes for estimating internal and external radiation doses from canal construction. The outcome was the EAREM code for external dose estimation and the INREM code for internal dose estimation, especially written for modes of exposure expected to be important and requiring the types of input information expected from other participants in the bioenvironmental study. These codes were used in preliminary estimates of potential dose to determine the relative importance of the modes of exposure and the relative hazard of various radionuclides. Both the specific activity and the environmental systems analysis approaches were analyzed and tested. Results of ORNL's Phase II participation have appeared in six publications.^{1.5-1.10}

Work in Phase III included final estimates of potential doses, assessments of these dose estimates with existing standards and guides, and the formulation of recommendations. The results of Phase III are reported in this document.

All aspects of this study could not be carried out in the most desirable manner. Some modes of exposure considered to be of potential importance by these authors could not be considered because the necessary inputs were not available. Also, changes in source terms and detonation programs made late in this study were not incorporated into the dose estimates listed in this report.

References for Chapter 1.0

1.1 A. W. Klement, Jr., Radiological Safety Research for Nuclear Excavation Projects — Interoceanic Canal Studies, in Proceedings for the Symposium on Public Health Aspects of Peaceful Uses of Nuclear Explosives, SWRHL-82, Las Vegas, Nevada, April 7-11, 1969.

1.2 M. M. Williamson, Nuclear Cratering Applications, in Proceedings for the Symposium on Public Health Aspects of Peaceful Uses of Nuclear Explosives, SWRHL-82, Las Vegas, Nevada, April 7-11, 1969.

1.3 Battelle Memorial Institute, Bioenvironmental and Radiological Safety Feasibility Studies Atlantic-Pacific Interoceanic Canal, BMI-171-003 (January 13, 1967).

1.4 K. E. Cowser, S. V. Kaye, P. S. Rohwer, W. S. Snyder and E. G. Struxness, Dose-Estimation Studies Related to Proposed Construction of an Atlantic-Pacific Interoceanic Canal with Nuclear Explosives: Phase I, ORNL 4101 (March 1967).

1.5 S. V. Kaye and D. J. Nelson, Nuclear Safety 9, 53 (1968).

1.6 W. D. Turner, S. V. Kaye, and P. S. Rohwer, EXREM and INREM Computer Codes for Estimating Radiation Doses to Populations from Construction of a Sea-Level Canal with Nuclear Explosives, K-1752 (September 16, 1968).

1.7 S. V. Kaye and S. J. Ball, "Systems Analysis of a Coupled Compartment Model for Radionuclide Transfer in a Tropical Environment," p. 731 in Symposium on Radioecology, ed. by D. J. Nelson and F. C. Evans, CONF-670503 (March 1969).

1.8 S. V. Kaye, P. S. Rohwer, K. E. Cowser and W. S. Snyder, BioSci. 19 (3), 238 (1969).

1.9 P. S. Rohwer and S. V. Kaye, BioSci. 19 (4), 326 (1969).

1.10 W. D. Turner, The EXREM II Computer Code for Estimating External Doses to Populations from Construction of a Sea-Level Canal with Nuclear Explosives, CTC-8 (July 21, 1969).

1.11 S. G. Bloom, A. A. Levin, W. E. Martin, and G. E. Raines, Mathematical Methods for Evaluating the Transport and Accumulation of Radionuclides, BMI-171-030 (April 3, 1970).

2.0 INFORMATION USED FOR ESTIMATING DOSE

2.1 Nuclear Explosives and Radionuclide Production

Radionuclide production (Ci) from a nuclear cratering detonation depends on the yield (TNT equivalent) of the device, the fission to fusion ratio, the materials used in constructing the device, and the grout, casing, stemming, soil, rock, and moisture at the site of detonation. When all important factors are identified, quantitative predictions can be made of the radionuclides that will be produced in a specified cratering detonation. The inventory of radionuclides after detonation includes fission products, fusion products, device activation products, soil and rock activation products, and residual fissionable materials. A basic source term list of 318 radionuclides was prepared by BCL from information provided by the Lawrence Radiation Laboratory (LRL) for use in the canal feasibility study.

2.1.1 Source Term for External Dose

Radionuclides present in quantities of 1 Ci or less at 1 hour after detonation were deleted by BCL from the basic list of 318 radionuclides. This deletion reduced the source term list to 205 radionuclides. The list was reduced further to 162 radionuclides with the elimination of radionuclides having radioactive half-lives of 10 minutes or less. Other considerations resulted in deleting 14 more radionuclides and adding 22 daughter radionuclides formed from the decay of parents produced by the detonation. Thus, the final source term for the estimation of external dose totaled 170 radionuclides (see Appendix I).

2.1.2 Source Term for Internal Dose

The basic source term of 318 radionuclides was reduced by BCL to approximately 70 by eliminating from further internal dose considerations all radionuclides present in quantities of 1 Ci or less 30 days after each detonation. Battelle further reduced the list of 31 radionuclides on the basis of their own estimates of potential internal dose due to ingestion. These dose estimates were obtained by calculations based on the specific-activity and standard-man critical-organ concepts, starting with the inventory of radionuclides present in quantities greater than 1 Ci 30 days after each detonation. Results of the calculations led BCL to conclude that approximately 40 radionuclides could be dropped from further consideration at this step because the total dose commitment would not exceed 1 rem in 70 years. The internal dose estimates presented in this report are summed dose contributions from the remaining 31 radionuclides listed in Table 2.1.

2.1.3 Detonation Programs Assumed for Routes 17 and 25

The detonation programs assumed for constructing a sea-level canal along Route 17 in Panama and Route 25 in Colombia are shown in Table 2.2. Besides being unevenly spaced in time, the yield of individual detonations varies with the excavation requirements of each detonation site.

Twenty-two detonations are assumed for Route 17, with the last detonation occurring 938 days (2.57 years) after the initial detonation. The time between detonations varies from less than one month for parts of the schedule to 152 days between detonations 10 and 11, 210 days between detonations 20 and 21, and 160 days between detonations 21 and 22.

Table 2.1. Radionuclide Lists for Internal Dose

ROUTE 17			ROUTE 25		
^3H	$^{127\text{m}}\text{Te}$	^{188}W	^3H	$^{127\text{m}}\text{Te}$	^{185}W
^{14}C	$^{129\text{m}}\text{Te}$	^{195}Au	^7Be	$^{129\text{m}}\text{Te}$	^{188}W
^{32}P	^{132}Te	^{196}Au	^{14}C	^{132}Te	^{195}Au
^{89}Sr	^{131}I	^{203}Hg	^{32}P	^{131}I	^{196}Au
^{90}Sr	^{141}Ce	^{210}Pb	^{90}Sr	^{141}Ce	^{203}Hg
^{95}Zr	^{144}Ce	^{238}Pu	^{95}Zr	^{144}Ce	^{210}Pb
^{95}Nb	^{143}Pr	^{239}Pu	^{103}Ru	^{143}Pr	^{239}Pu
^{103}Ru	^{151}Sm	^{240}Pu	^{106}Ru	^{147}Nd	^{240}Pu
^{106}Ru	^{155}Eu	^{241}Pu	$^{115\text{m}}\text{Cd}$	^{151}Sm	^{241}Pu
^{124}Sb	^{181}W		^{124}Sb	^{155}Eu	
^{125}Sb	^{185}W		^{125}Sb	^{181}W	

Table 2.2. Detonation Programs Assumed for Routes 17 and 25

Detonation Number	ROUTE 17			ROUTE 25		
	Days Since First Detonation	Number of Devices	Total Yield (Mt)	Days Since First Detonation	Number of Devices	Total Yield (Mt)
1	0	6	16.0	0	9	9.8
2	38	4	20.0	21	4	13.0
3	47	4	17.0	45	4	25.0
4	72	4	30.0	91	6	14.0
5	95	31	11.6	141	4	11.0
6	126	6	9.5	170	4	14.0
7	139	13	5.8	199	5	10.0
8	156	34	11.0	380	10	10.0
9	194	50	7.6	395	4	25.0
10	212	10	14.0	441	7	10.0
11	364	20	8.4	489	4	14.0
12	373	5	12.0	511	7	9.0
13	381	4	22.0	531	5	10.0
14	405	10	11.5	543	<u>13</u>	<u>11.0</u>
15	452	4	14.0	Total	86	195.8
16	461	15	12.0			
17	490	50	5.2			
18	508	50	8.8			
19	527	10	10.5			
20	566	7	10.0			
21	776	50	10.4			
22	938	<u>50</u>	<u>7.5</u>			
Total		437	274.8			

Although only 14 detonations are assumed for Route 25, the schedule is divided into two passes, the first terminating after 199 days and the second beginning 181 days later and terminating 543 days after the first detonation.

2.2 Locations for Computing Dose

Patterns and levels of fallout that might result from nuclear excavation of a canal along Routes 17 and 25 were computed by the Environmental Science Services Administration (ESSA). Later, ESSA revised their estimates after establishment of a revised detonation program. The predicted levels of contamination present at each of the fallout contour lines were used by ESSA to estimate the potential cumulative gamma exposure resulting after 70 years at a height of 3 ft above the land surface. The exclusion boundary that was selected lies outside the 0.1 R contour for a 70-year exposure to external gamma radiation from the landsurface. Theoretically, if ESSA's predicted exposures are realistic and if populations are evacuated from the exclusion area during and following canal construction, no individual or population group would be expected to receive a lifetime external gamma exposure greater than 0.1 R. Figures 2.1 and 2.2 show the location and extent of ESSA's exclusion area for Routes 17 and 25, respectively.

2.2.1 External Dose (Route 17)

Thirteen locations (Fig. 2.1), all within the exclusion zone, were evaluated for external dose and dose rate with the EXREM code. Since resident populations will be evacuated from the exclusion zone before the first detonation, estimates of external dose are important

Fig. 2.1. Map of Panama Illustrating the Route 17 Alignment, Watersheds (numbered 1 through 7), and Locations of Towns and Villages for Estimates of External Dose.

primarily for two considerations: 1) determination of the radiological safety for construction personnel and 2) as an aid to determination of the time when the resident population may return to each location.

Battelle Columbus Laboratories multiplied the quantity of each radionuclide produced at the time of each detonation by an assumed local fallout fraction of 15 percent and a factor representing the fraction of the fallout pattern deposited on a unit area basis at each of the 13 point locations. The 13 point locations were superimposed on a map of ESSA's fallout fraction contours enclosing each location and the higher of the two fallout contours was used by BCL to compute areal deposition on the land surface in $\mu\text{Ci}/\text{cm}^2$. This selection of the higher contour value can result in an overestimate of dose by as much as a factor of 10, which is the greatest difference between fallout fractions for two contours enclosing any of the 13 locations.

2.2.2 Internal Dose (Routes 17 and 25)

Land areas adjacent to the two proposed canal alignments were divided into watersheds by BCL, and ESSA's fallout contours were used to compute an average radionuclide concentration on the land surface of each watershed. These watersheds are outlined by dashed lines in Fig. 2.1 (Route 17) and Fig. 2.2 (Route 25). Internal dose was estimated for the watershed along each route predicted to have the highest initial fallout concentration on the land surface, e.g., watershed 5 for Route 17 and watershed 2 for Route 25. Since no unique physiographic or biotic factors were considered in estimating potential internal doses to residents of these two watersheds,

Fig. 2.2. Map of Colombia Illustrating the Route 25 Alignment and Watersheds (numbered 1 through 5).

the initial average fallout concentrations were normalized to watershed 5 for Route 17 and watershed 2 for Route 25 to derive a table of factors to extrapolate doses to all other watersheds (see Table 2.3).

Radioactivity intakes leading to internal exposures were assumed to result from a composite diet representing food and beverages collected from the entire watershed. Thus, our calculated internal doses are average values for the entire watershed and are not related to any particular point location within the watershed. This is in contrast to the use of point locations (towns and villages) for the computation of potential external doses.

2.3 Modes of Exposure

2.3.1 External Exposure (Route 17)

A "mode of exposure" is the manner in which a person is exposed. Originally, it was hoped that input would be provided to estimate potential external doses from three modes of exposure: exposure above a contaminated land surface, submersion in a radioactive "cloud," and submersion in contaminated water. Although the EXREM code was developed to compute external doses for all three modes of exposure, BCL program changes limited input data only to exposure above a contaminated land surface, and this only for Route 17. In view of time and budget limitations, the other two modes of exposure were not considered.

The duration of potential submersion in a radioactive "cloud" is limited to the length of time required for the cloud to pass over the location of interest. This time may range from less than one hour

Table 2.3. Correction Factors Compiled by BCL for Estimating Potential Radiation Doses in Different Watersheds Near Routes 17 and 25^a

Watershed	Correction Factor	
	Route 17	Route 25
5	1.00	--
6	0.395	--
7	0.437	--
1	0.284	0.0000964
4	0.0158	0.474
2	0.00105	1.00
3	0.000263	0.826

^aA comparable correction factor for areas corresponding to the 0.1 Roentgen exposure contour designated by ESSA equals 0.0013 for Route 17 and 0.000505 for Route 25. The decimal places are not indicative of accuracy.

to approximately one day, depending upon weather conditions and distance from the canal. In any event, the duration of submersion, and hence exposure, is relatively short since people will be evacuated from the area expected to be covered by local fallout while the nuclear excavation is being carried out, submersion in the "cloud" is not anticipated unless the "cloud" or "clouds" fail to disperse as predicted. In contrast, some finite exposure to contaminated landscape is possible, even many years after people return to the exclusion area. At the time of reentry, rivers and streams should be flushed of almost all fallout radioactivity, so that even a high use factor for surface water may not result in an appreciable external dose from submersion in contaminated water.

Most radiological safety assessments do not consider the potential external dose from beta emitters deposited on landscape because clothing and other materials provide adequate shielding. Since many Panamanians and Colombians wear little clothing, it may be important to estimate exposures to skin from beta emitters. The Cuna Indians of the San Blas Islands and the mainland of eastern Panama have the highest incidence of albinism in the world, representing a potentially "critical" population group for beta skin doses. The albinos numbered approximately 150 individuals in 1962.^{2.1} They are considered to be especially susceptible to the effects of skin irradiation because they have a high incidence of chronic skin lesions caused by sunburn. Seborrheic keratoses, solar elastoses, and carcinomas of squamous and basal cell origin have been reported as commonly occurring in Cuna Albinos.^{2.2, 2.3} Therefore, we undertook to estimate dose to the skin from beta emitters deposited directly on the skin and on the land surface.

2.3.2 Internal Exposure (Routes 17 and 25)

Ingestion and inhalation are the primary modes of internal exposure following release of radioactivity to the environment. There are additional modes of internal exposure but they are of less importance generally; absorption of radionuclides through the skin and entry through wounds are examples.

Radionuclide intake rates via ingestion ($\mu\text{Ci/day}$, as a function of age- and time-dependent variations) were provided for internal dose estimations with the INREM computer code. These input data for INREM were BCL's estimates of radionuclide intakes which could result from the consumption of contaminated foods and beverages (animals other than fish, fish, plant edibles, and water) by people living near Routes 17 and 25. Input data for other modes of internal exposure were not available because of program limitations, but ingestion is probably the most important internal exposure mode in any case. That is, if one assumes that evacuation of the exclusion area is successful in preventing inhalation exposures. However, it is important to note that the evaluation of only one internal exposure mode may result in an underestimate of the potential internal radiation dose.

2.4 Population Data for Estimating Genetically Significant Dose

Parameters in the model used to estimate the genetically significant dose were evaluated for both routes with the Panamanian data of Arauz.^{2.4} Sufficient demographic data were not provided to complete a unique evaluation for populations living in

the vicinity of Route 25 in Colombia. The territory studied by Arauz covers 23,000 square kilometers and, according to the 1960 census, has 25,700 inhabitants of various ethnic backgrounds. A nonrandom sample, including some 1,400 houses and approximately 8,400 individuals among these ethnic groups, were examined. Four clearly distinct populations were identified: Cuna Indians, Choco Indians, Negroes, and Colonists. Breakdown of the sample was as follows:

<u>Population</u>	<u>Men</u>	<u>Women</u>	<u>Total</u>
Cuna Indians	1,200	1,300	2,500
Choco Indians	1,400	1,200	2,600
Negroes	1,300	1,200	2,500
Colonists	400	400	800
	<hr/> 4,300	<hr/> 4,100	<hr/> 8,400

Details concerning age distribution and birth rate for each population are summarized in Table 2.4. It is assumed that the population statistics of this sample are representative of the respective populations. The birth rate values in Table 2.4 are specific for females; however, in the absence of better information, the same values were also applied to the male population when estimating genetically significant dose.

2.5 Age-Dependent Parameters for Internal Dose

A thorough assessment of population exposures would require radiation dose estimates for each individual or for each critical segment or group in the whole population.

Table 2.4. Age Distributions and Birth Rates for Populations Indigenous to Route 17

Age Range (years)	Age Distribution & Birth Rate							
	Cuna Indians		Choco Indians		Negroes		Colonists	
	Percent of Cuna Population	Birth ^a Rate	Percent of Choco Population	Birth ^a Rate	Percent of Negro Population	Birth ^a Rate	Percent of Colonist Population	Birth ^a Rate
< 5	16.5	0	21.2	0	20.5	0	21.7	0
5- 9	16.9	0	16.8	0	20.3	0	18.6	0
10-14	13.4	0	13.3	0	14.1	0	12.1	0
15-19	10.4	0.18	10.6	0.26	7.5	0.29	8.0	0.23
20-24	7.8	0.30	8.1	0.39	6.2	0.41	7.8	0.36
25-29	8.2	0.27	7.5	0.34	4.8	0.36	9.9	0.31
30-34	7.7	0.20	5.6	0.23	5.2	0.22	5.7	0.21
35-39	5.7	0.13	4.8	0.13	5.0	0.09	5.4	0.12
40-44	3.7	0.06	2.7	0.07	3.4	0.04	2.3	0.05
45-49	3.1	0.02	2.7	0.02	4.0	0.02	3.5	0.02
> 50	6.5	0	6.7	0	8.9	0	4.9	0

^aBirth rate = live births per year per woman.

A practical approach to such an assessment is to divide the population into groups, the groups being small and homogeneous with respect to the factors which influence dose. Age is an important factor in this regard, and, although other differentiating factors may also be operative, age is a convenient characteristic with which to differentiate population groups. Therefore, the indigenous populations in Panama and Colombia were divided into five age groups: 0 to 1 year, 1 to 5 years, 5 to 10 years, 10 to 15 years, and greater than 15 years. These age intervals were selected jointly by ORNL and BCL, with cognizance of the dietary data provided by Arauz, and McBryde and Costales.^{2.5, 2.6} The paucity of information describing human populations in Panama and Colombia and their age-dependent characteristics led to heavy reliance on the tabulated values of "standard" man,^{2.7} even for this limited age breakdown, recognizing that populations in Central America may differ considerably from "standard" man. Differences among the four ethnic groups are reflected in their daily intakes of radioactive materials.

Age-dependent dose estimates were obtained with the INREM code for total body, bone, liver, thyroid, testes, ovaries, lungs, kidneys, and G.I. tract. Organs were selected on the basis of the importance of estimates of their doses to a radiological safety assessment, and the availability of information to complete organ-specific dose calculations. In those instances where it was desirable to estimate the dose to an organ for which an organ-specific dose estimate was not provided by the INREM code, estimated total-body dose was applied. Estimation of dose to bone due to tritium was an exception, in that case one-fourth of the total-body dose was applied. Tritium was assumed to be present in

the body as HTO, and to be in equilibrium with the body water pool. Dose to an organ due to HTO was assumed to be proportional to the percent water content (by weight) of that organ. Most tissues and organs are approximately 60 to 80 percent water; bone is an exception, being approximately 20 percent water.^{2.8}

Dose estimation models in the INREM code can utilize age-dependent information for organ mass (m), effective absorbed energy (ϵ), fraction of radionuclide intake reaching the reference organ (f), effective half-time of the radionuclide in the reference organ (T_e), and daily radionuclide intake (I). The following sections outline the rationale used to determine the values of these age-dependent parameters.

2.5.1 Organ Mass

Values chosen for organ mass as a function of age were based on literature describing the Caucasian population from which values for standard man are drawn. Caucasian population values for all age groups except the 0 to 1 year olds were reduced 20 percent to account for the smaller physical size observed in those groups in Central American populations.^{2.9} A notable exception is the thyroid, in which case no mass reduction was made because of the high incidence of goiter.^{2.9} Individuals achieve adult physical maturity by the age of 15 years. The values for organ mass are tabulated in Table 2.5.

2.5.2 Effective Absorbed Energy

Effective absorbed energy contributions of all radiation emissions, except gamma and x-ray photons, were assumed to be independent of the age of the individual exposed. Preliminary results

Table 2.5. Variations in Organ Mass as a Function of Age

Body Organ	Organ Mass (g)				
	0-1 year	1-5 years	5-10 years	10-15 years	greater than 15 years
Total Body ^a	7,800	11,600	20,400	34,400	56,000
Bone ^{b,c}	500	800	1,120	2,720	3,800
Liver ^{d,e}	230	400	600	800	1,440
Kidneys ^f	50	80	110	150	240
Thyroid ^g	2.0	2.5	5.0	11.3	16.0
Testes ^e	3.4	3.4	4.2	12.0	32.0
Ovaries ^e	0.4	1.0	2.0	4.8	8.0
Lungs ^h	110	190	300	410	800
GI Tract (Contents) ^{i,j,k}					
Stomach	28	50	88	136	200
Small Intestine	60	101	129	181	320
Upper Large Intestine	33	55	71	99	176
Lower Large Intestine	20	34	44	61	108

Table 2.5. (cont'd)

- ^aH. W. Stoudt, A. Damon, and R. A. McFarland, *Human Biology* 32, 331 (1960).
- ^bM. Muhlmann, *Ergebn. d. Anat. u. Entwicklungsgesch* 27, 1 (1927).
- ^cG. G. Robertson, "Developmental Anatomy," p. 92 in Morris Human Anatomy, 12th ed., ed. by B. J. Anson, McGraw-Hill, New York (1966).
- ^dE. Boyd, *Arch. Pathol.* 16, 350 (1933).
- ^eE. R. Roessle and F. Roulet, Mass und Zahl in der Pathologie, Springer-Verlag, Berlin (1932).
- ^fWhite House Conference, p. 509 (1933).
- ^gY. Mochizuki, K. Mowafy, and B. Pasternack, *Health Physics* 9, 1299 (1963).
- ^hE. Boyd, An Introduction to Human Biology and Anatomy for First-Year Medical Students, Dept. for Study of Human Growth, University of Colorado School of Medicine (1952).
- ⁱR. E. Scammon, *Amer. J. of Diseases of Childhood* 17, 395 (1919).
- ^jR. E. Scammon, The Measurement of the Body in Childhood, Univ. of Minnesota Press (1930).
- ^kI. S. Eve, *Health Physics* 12, 131 (1966).

from energy absorption studies being conducted in the Health Physics Division at ORNL suggest that absorbed fractions within organs for gamma and x-ray photons are approximately proportional to the one-third power of organ mass.^{2.10} Therefore, the effective absorbed energy contributions of those photons are adjusted in proportion to the one-third power of the ratio of organ mass for a given age group to the mass of the respective organ of "standard" man given in ICRP Publ. 2.^{2.7} Data given for the G.I. tract are appropriate for the segments identified in ICRP Publ. 2 as critical for the respective radionuclides. The values of effective absorbed energy are listed in Table 2.6.

2.5.3 Fraction of Intake Reaching Organ of Reference

There is little information available on the age-dependent variation of radionuclide uptake by body organs. Adequate data are not available for specific age-group evaluations for most radionuclides under consideration, and, in those cases, standard-man values were applied to all age groups.^{2.7} The fractional uptake values used, which differ from those for "standard" man, are presented in Table 2.7. The application of standard-man values to all age groups is not conservative necessarily; however, it does not seem prudent to use other values without supporting literature. In those cases where uptake fractions for standard man are large (approaching 1.0) the values may be applied to younger age groups with confidence. However, when uptake fractions for standard man are smaller, application of the values to younger age groups must be done with greater reservation, because there is no certainty that body processes controlling uptake are equally discriminating for all age groups, particularly for infants.

Table 2.6. Variations in Effective Absorbed Energy as a Function of Age

Radio-nuclide	Body Organ	Effective Absorbed Energy (MeV)				
		0-1 year	1-5 years	5-10 years	10-15 years	greater than 15 years
^{95}Zr	Total Body	0.62	0.68	0.78	0.89	1.01
	Bone	1.04	1.05	1.06	1.09	1.10
	Liver	0.39	0.44	0.47	0.50	0.56
	Kidneys	0.32	0.34	0.35	0.37	0.40
	Lungs	0.36	0.40	0.43	0.45	0.51
	GI Tract	0.27	0.28	0.29	0.32	0.34
^{95}Nb	Total Body	0.28	0.31	0.36	0.42	0.47
	Bone	0.33	0.34	0.34	0.35	0.36
	Liver	0.17	0.19	0.21	0.22	0.25
	Kidneys	0.14	0.15	0.16	0.17	0.19
	Lungs	0.16	0.18	0.20	0.21	0.25
	GI Tract	0.11	0.12	0.13	0.14	0.15
^{103}Ru	Total Body	0.26	0.28	0.32	0.37	0.42
	Bone	0.56	0.57	0.58	0.59	0.60
	Kidneys	0.15	0.16	0.17	0.18	0.21
	Lungs	0.16	0.17	0.18	0.20	0.23
	GI Tract	0.16	0.17	0.18	0.18	0.20
^{106}Ru	Total Body	1.37	1.39	1.39	1.40	1.40
	Bone	6.5	6.5	6.5	6.5	6.5
	Kidneys	1.33	1.33	1.34	1.34	1.35
	Lungs	1.33	1.34	1.35	1.35	1.36
	GI Tract	1.32	1.32	1.33	1.33	1.33
^{124}Sb	Total Body	0.93	1.03	1.17	1.33	1.51
	Bone	1.86	1.91	1.95	2.09	2.16
	Liver	0.63	0.69	0.74	0.79	0.89
	Thyroid	0.43	0.44	0.48	0.53	0.57
	Lungs	0.60	0.66	0.72	0.76	0.89
	GI Tract	0.50	0.54	0.56	0.59	0.64

Table 2.6. (cont'd.)

Radio-nuclide	Body Organ	Effective Absorbed Energy (rEV)				
		0-1 year	1-5 years	5-10 years	10-15 years	greater than 15 years
^{125}Sb	Total Body	0.22	0.24	0.27	0.30	0.35
	Bone	0.50	0.51	0.53	0.57	0.58
	Liver	0.16	0.18	0.19	0.20	0.22
	Thyroid	0.11	0.12	0.12	0.13	0.15
	Lungs	0.15	0.17	0.18	0.19	0.22
	GI Tract	0.22	0.24	0.26	0.28	0.30
^{127m}Te	Total Body	0.27	0.28	0.29	0.30	0.32
	Bone	1.24	1.27	1.30	1.38	1.42
	Liver	0.27	0.28	0.29	0.30	0.32
	Kidneys	0.27	0.28	0.29	0.30	0.32
	Thyroid	0.26	0.26	0.27	0.29	0.30
	Testes	0.26	0.26	0.26	0.28	0.31
	Lungs	0.27	0.28	0.29	0.30	0.32
	GI Tract	0.28	0.29	0.30	0.31	0.32
^{129m}Te	Total Body	0.82	0.87	0.92	0.98	1.05
	Bone	3.1	3.1	3.1	3.2	3.2
	Liver	0.71	0.74	0.76	0.77	0.82
	Kidneys	0.70	0.71	0.72	0.74	0.76
	Thyroid	0.64	0.64	0.65	0.67	0.68
	Testes	0.64	0.64	0.64	0.66	0.67
	Lungs	0.71	0.74	0.76	0.77	0.82
	GI Tract	0.64	0.67	0.69	0.70	0.75
^{132}Te	Total Body	1.16	1.26	1.42	1.60	1.80
	Bone	2.67	2.72	2.76	2.90	2.96
	Liver	0.80	0.86	0.92	0.96	1.07
	Kidneys	0.74	0.79	0.82	0.86	0.92
	Thyroid	0.60	0.61	0.64	0.70	0.72
	Testes	0.59	0.59	0.60	0.65	0.71
	Lungs	0.77	0.84	0.90	0.94	1.07
	GI Tract	0.61	0.64	0.66	0.70	0.80

Table 1.6. (cont'd.)

Radio-nuclide	Body Organ	Effective Absorbed Energy (Mrd)				
		0-1 year	1-5 years	5-10 years	10-15 years	Greater than 15 years
^{131}I	Total Body	0.32	0.35	0.35	0.38	0.43
	Thyroid	0.21	0.22	0.22	0.23	0.25
	Lungs	0.25	0.26	0.27	0.28	0.31
	GI Tract	0.23	0.23	0.24	0.24	0.25
^{141}Ce	Total Body	0.19	0.19	0.20	0.21	0.21
	Bone	0.81	0.81	0.81	0.82	0.82
	Liver	0.13	0.13	0.13	0.13	0.13
	Kidneys	0.17	0.18	0.18	0.18	0.18
	Lungs	0.17	0.18	0.18	0.18	0.18
	GI Tract	0.17	0.17	0.17	0.17	0.17
^{144}Ce	Total Body	1.26	1.27	1.27	1.27	1.27
	Bone	6.25	6.25	6.25	6.25	6.25
	Liver	1.26	1.26	1.26	1.26	1.26
	Lungs	1.26	1.26	1.26	1.26	1.26
	GI Tract	1.26	1.26	1.26	1.26	1.26
^{151}Sm	Total Body	0.032	0.034	0.036	0.039	0.041
	Bone	0.12	0.13	0.13	0.13	0.13
	Liver	0.033	0.035	0.037	0.038	0.041
	Kidneys	0.032	0.034	0.036	0.039	0.041
	Lungs	0.032	0.034	0.036	0.037	0.041
	GI Tract	0.032	0.034	0.035	0.037	0.039
^{155}Eu	Total Body	0.11	0.12	0.13	0.14	0.16
	Bone	0.27	0.27	0.27	0.28	0.28
	Liver	0.073	0.078	0.082	0.085	0.093
	Kidneys	0.063	0.071	0.073	0.076	0.080
	Lungs	0.072	0.076	0.080	0.084	0.093
	GI Tract	0.063	0.066	0.067	0.069	0.072
^{181}La	Total Body	0.10	0.12	0.14	0.16	0.19
	Bone	0.020	0.023	0.026	0.034	0.039
	Liver	0.045	0.054	0.062	0.068	0.083
	Lungs	0.045	0.054	0.059	0.065	0.081
	GI Tract	0.024	0.029	0.031	0.035	0.042

Table 2.6.(cont'd.)

Radio-nuclide	Body Organ	Effective Absorbed Energy (MeV)				
		0-1 year	1-5 years	5-10 years	10-15 years	greater than 15 years
^{188}W	Total body	0.85	0.85	0.87	0.89	0.93
	Bone	3.80	3.80	3.81	3.81	3.81
	Liver	0.89	0.89	0.90	0.90	0.92
	Lungs	0.89	0.89	0.90	0.90	0.92
	GI Tract	0.78	0.78	0.78	0.78	0.78
^{203}Hg	Total Body	0.18	0.19	0.21	0.22	0.24
	Liver	0.14	0.15	0.16	0.16	0.17
	Kidneys	0.13	0.14	0.14	0.15	0.15
	Lungs	0.14	0.15	0.15	0.16	0.17
	GI Tract	0.13	0.13	0.13	0.14	0.14

2.5.4 Effective Half-Time

Effective half-time is another of the age-dependent parameters in the INREM code for which descriptive data are scarce. Age-dependent values were used for ^3H ^{2.11} and ^{131}I ^{2.12} (see Table 2.8), and standard-man values were applied to all age groups for other radionuclides. ^{2.7} The application of standard man values to younger age groups is probably conservative in most, if not all, cases. At least a slight increase in effective half-time as the individual ages would be anticipated for most radionuclides, because the basal metabolic rate of man decreases with increasing age. ^{2.13} Increases in effective half-times accompanying increases in age of the individual have been observed for several radionuclides (^3H and ^{131}I are examples, see Table 2.7).

2.5.5 Daily Radionuclide Intake

Daily radionuclide intake information was determined by BCL with the aid of multicompartmental models simulating the environmental transfer of radionuclides in study areas of Panama and Colombia. ^{2.14} The kinds and amounts of food item consumed were determined by an extensive census of the indigenous populations. ^{2.5,2.6}

2.6 Assumptions for Computing External Beta Dose to the Skin

Most assumptions concerning the potential external exposure of indigenous populations to beta emitters are more tenuous than those underlying the hypothetical exposures to gamma emitters. If indeed, only the expected exposure situations are encountered (i.e., reentry to the exclusion area sometime following the last detonation), then the external exposure to beta emitters would probably

Table 2.7. Variations in the Fraction of Ingested ^{89}Sr and ^{131}I Reaching the Reference Organs as a Function of Age

Radio-Nuclide	Reference Organ	Fraction of Ingested Radioactivity Reaching the Reference Organ:				
		0-1 year	1-5 years	5-10 years	10-15 years	greater than 15 years
$^{89}\text{Sr}^a$	Total Body	0.20	0.10	0.13	0.4	0.3
	Bone	0.14	0.07	0.09	0.28	0.17
$^{131}\text{I}^b$	Total Body	1.0	1.0	1.0	1.0	1.0
	Thyroid	0.3	0.3	0.3	0.3	0.3

^aEstimated from work of S. R. Bernard, Health Physics Division Annual Progress Report, July 31, 1965, ORNL-3849, pp. 195-201 (October 1965).

^bFederal Radiation Council, Background Material for the Development of Radiation Protection Standards, Report No. 2, U.S. Govt. Ptg. Off., Wash., D. C. (Sept. 1961).

Table 2.8 Variations in Effective Half-Time (days) of Tritium and ^{131}I as a Function of Age

Radio-Nuclide	Reference Organ	Effective Half-Time (days)				
		0-1 year	1-5 years	5-10 years	10-15 years	greater than 15 years
$^3\text{H}^a$	Total Body	3.2	4.4	4.9	6.3	9.5
	Total Body	4.0	5.0	6.0	6.5	7.0
$^{131}\text{I}^b$	Thyroid	4.0	5.0	6.0	6.5	7.0

^aP. S. Rohwer and S. V. Kaye, Age Dependent Models for Estimating Internal Dose in Feasibility Evaluations of Plowshare Events, ORNL-TM-2229 (April 1968).

^bM. J. Cook and W. S. Snyder, Health Physics Division Annual Prog. Report, July 31, 1965, ORNL-3849, pp. 190-93 (October 1965).

be negligible. This conclusion is possible because 1) the deposition of beta emitters directly on the skin of humans is not expected, and 2) beta emitters deposited on the landscape probably will have infiltrated at least the top soil layers due to normal weathering. Even a small amount of radionuclide infiltration into soil and litter would effectively shield the beta emitters, while having but a negligible effect on gamma emitters.

Generally, it appears that only the exposure to fresh fallout is important for beta skin-dose considerations. External exposure to beta emitters might develop in the unlikely event that a "cloud" deposits fresh fallout over an inhabited area (i.e., outside the exclusion area). It was primarily with this possibility in mind that potential beta doses to the skin were computed. Because of rapid weathering effects in the tropical environment, the time during which external exposure to beta radiation might be important is probably short. Also, radioactivity deposited on skin is not likely to remain there very long--probably less than one week.

Dose to the skin from beta emitters was assessed for radionuclides deposited on the land surface and on the surface of human skin. The germainal or basal layer of the epidermis is usually regarded as the most radiosensitive layer of the skin.^{2.15} Over most parts of the body, the basal layer is approximately 0.1 mm below the surface, but on the palms of the hands and feet the depth of the basal layer is approximately 0.6 mm.^{2.16} Albino Cuna Indians of eastern Panama develop actinic keratoses by the age of three.^{2.3} Thus, there is thickening of the skin in areas exposed to sunlight; these same areas would probably be affected by beta emitters. The

increased depth of the basal layer due to actinic keratoses may vary considerably depending on the severity of the affliction. A depth of 1 mm was chosen arbitrarily to represent the depth of the critical tissue (basal layer) in the skin of albino Cuna Indians. These albinos probably are the critical group for this mode of exposure (if all populations are assumed to be equally exposed), because their skin is already in an injured state. This conclusion seems reasonable despite the slight increase in shielding of the basal layer due to thickening of the corneum. Whitton^{2.15} has stated that,---"wounded skin is probably more susceptible to radiation damage than normal skin, but it is impossible to make any quantitative estimation of the degree of susceptibility."

2.7 Special Radiological Protection Considerations

Radiation dose estimates must be in a form suitable for comparison with the appropriate radiation safety criteria. The radiation safety criteria suggested for this study are given in terms of dose equivalent rates (rem/year) and total dose equivalents (rem/30 years, rem/70 years) for total body and various parts thereof.^{2.17} Dose equivalent rate and total dose equivalents for any part of the body are the sum of the dose equivalents contributed by both external and internal sources.

2.7.1 Simultaneous Internal Exposure of Multiple Organs

Estimation of total internal radiation dose to a given organ for the projected canal exposure situation requires the addition of dose contributions from many radionuclides. The "critical organ" concept of the ICRP is the basis for this approach; the critical organ being defined as that organ whose damage by radiation results in the greatest

damage to the individual or his descendants.^{2.18} Dose estimates for nine body organs were obtained with the INREM code to facilitate the assessment of hypothetical exposure situations in terms of the appropriate radiation safety guides.

Addition of doses to different organs presents another problem. The ICRP states: "Exposure to radioactive materials in the environment may entail significant exposures of several organs. Under such conditions the situation is somewhat comparable to that of irradiation of the whole body. The additional risk when several organs are involved needs to be recognized, although our present knowledge does not permit precise evaluation."^{2.18}

The additivity of doses to reference organs requires the assumption that exposures to different parts of the body are not synergistic, i.e., that the radiation response of one part is not affected by the radiation exposure received by another part. The ICRP suggests that an exposure should be considered as excessive if three or more organs are exposed at more than one-half their respective Maximum Permissible Doses.^{2.18}

2.7.2 Additivity of Internal and External Dose

Potential total dose to an individual from specified sources is estimated by summing the doses from all external and internal exposures. Keep in mind that all modes of exposure were not evaluated in this study, and that estimates of potential total dose in this report include only dose contributions from external exposure above the contaminated land surface and from internal exposure via ingestion of contaminated food and beverages.

Procedures for this addition in the case of occupational exposures have been suggested by the ICRP. One suggestion is found in ICRP Publ. 6:^{2.19} "The Commission has considered the difficulty of making proper allowance for the addition of doses from penetrating external exposure and from internal exposure in the case of long-lived bone-seeking isotopes, in view of the use for them of the "n" factor. For these radionuclides the Commission recommends that (i) if the estimated body-burden is less than one-half of the maximum permissible, no consequential restriction of external radiation exposure need be applied; (ii) if the estimated body-burden is greater than one-half but less than the maximum permissible, the total body exposure to penetrating external radiation shall be limited to not more than 1.5 rems in any year; and if A years is the age of the individual when the body-burden was first found to exceed one-half of the maximum permissible, then the total accumulated dose from such future exposure beyond age A shall not exceed $1.5 (N - A)$ rems where N is the current age of the individual; if, however, at age B the body-burden is found to have dropped to less than one-half the maximum permissible value, the accumulated dose from future external total body exposure beyond age B shall not exceed $5 (N - B)$ rems; (iii) if the estimated body-burden equals or exceeds the maximum permissible, no occupational exposure to penetrating external radiation is permissible." Another suggestion, this one not specifically related to long-lived bone-seeking radionuclides and occupational workers, is found in ICRP Publ. 9:^{2.18} "If external exposure of the whole body has resulted in an excess of one-half of the Maximum Permissible Dose to the gonads or to the red bone-marrow, no two or more organs shall be exposed at more than one-half their respective Maximum Permissible Doses."

A more recent publication of the ICRP, Report of the Task Group on Spatial Distribution of Radiation Dose, briefly touches upon the additivity problem.^{2.20} A point is made of the fact that the present system of a large number of critical organs, most of which carry the same dose limit, is not a scheme based on risk considerations, and additivity rules are of necessity largely arbitrary. The Task Group, while supporting the above quoted views of the Commission, expressed the opinion that the suggested additivity procedures are sometimes applied too strictly.

2.7.3 Apportionment of Genetic Dose to Canal Excavation

Guidance is given in ICRP Report 1 suggesting that 1.5 rems of the genetic dose limit of 5 rems/30 years should be kept in reserve and not apportioned to any presently recognized exposure applications.^{2.21} Thus, we are left with 3.5 rems/30 years, or 0.117 rem/year for actual apportionment to all sources except background and medical sources. Further guidance relevant to apportionment is given by the ICRP in Report 9^{2.22} as follows: "The Commission wishes to point out that it is important to ensure that no single type of population exposure takes up a disproportionate share of the total. The way in which this is done will depend upon circumstances which may vary from country to country, and will be determined by national, economic and social considerations." A disproportionate share of the genetic dose limit (or genetically significant dose) for a single type of exposure could conceivably be an allocation of one-half or more of the total amount to be apportioned (i.e., 0.117 rem/year). A maximum, one-half allocation for the canal construction project would leave approximately 60 mrem/year. Assessments of genetically significant dose in this

report are based on the full (5 rems/30 years) allocation. It seems prudent to these authors to assume that any nation's system of genetic dose apportionment, taking various economic and sociopolitical factors into account, would follow the guidance of the ICRP and result in reduced allocations of dose for any nuclear excavation project, the present one included.

References for Chapter 2.0

- 2.1 C. E. Keeler, J. Heredity 55, 115 (1964).
- 2.2 C. E. Keeler, The MSH Bulletin of Current Research 2, 8 (1963).
- 2.3 C. E. Keeler, "Albinism, Xeroderma Pigmentosum, and Skin," p. 349 in National Cancer Institute Monograph No. 10, Proceedings of the Conference on Biology of Cutaneous Cancer, Philadelphia, Penn., April 6-11, 1962.
- 2.4 R. T. de Arauz, Demographic Characteristics of Human Groups Inhabiting the Eastern Region of the Republic of Panama, (Feb. 23, 1968).
- 2.5 R. T. de Arauz, Bio. Sci. 19, 331 (1969).
- 2.6 E. W. McBryde and A. S. Costales, Bio. Sci. 19, 432 (1969).
- 2.7 International Commission on Radiological Protection, Recommendations of the International Commission on Radiological Protection (Report of Committee 2 on Permissible Dose for Internal Radiation), ICRP Publ. 2, Pergamon Press, London (1959).
- 2.8 H. Skelton, Arch. of Int. Med. 40, 140 (1927).
- 2.9 Interdepartmental Committee on Nutrition for National Defense, Colombia Nutrition Survey, U.S. Govt. Ptg. Off., Washington, D.C. (December 1961).
- 2.10 W. S. Snyder, Personal Communication.
- 2.11 P. S. Rohwer and S. V. Kaye, Age-Dependent Models for Estimating Internal Dose in Feasibility Evaluations of Plowshare Events, ORNL-TM-2229 (April 1968).

2.12 D. F. Bunch, Controlled Environmental Radioiodine Tests Progress Report Number 2, IDO-12053 (August 1966).

2.13 P. Barč (Ed.), Medical Physiology, 11th Ed., p. 378, The C. V. Mosby Company, St. Louis (1961).

2.14 S. G. Bloom, A. A. Levin, W. E. Martin, and G. E. Raines, Mathematical Methods for Evaluating the Transport and Accumulation of Radionuclides, BMI-171-030 (April 3, 1970).

2.15 J. T. Whitton, Biological Aspects of Skin Irradiation. Part I. Preliminary Investigations, RD/B/N/1355 (April 1969).

2.16 R. F. Rushmer, K. J. K. Buettner, J. M. Short, and G. F. Odland, Science 154, 343 (1966).

2.17 K. E. Cowser, S. V. Kaye, P. S. Rohrer, W. S. Snyder, and E. G. Strunness, Dose-Estimation Studies Related to Proposed Construction of an Atlantic-Pacific Interoceanic Canal with Nuclear Explosives: Phase I, ORNL-4101 (March 1967).

2.18 International Commission on Radiological Protection, Recommendations of the International Commission on Radiological Protection (Adopted September 17, 1965), ICRP Publ. 9, Pergamon Press, London (1965).

2.19 International Commission on Radiological Protection, Recommendations of the International Commission on Radiological Protection (as Amended 1959 and Revised 1962), ICRP Publ. 6, Pergamon Press, London (1964).

2.20 International Commission on Radiological Protection, Radiosensitivity and Spatial Distribution of Dose (Reports Prepared by Two Task Groups of Committee 1 of the International Commission on Radiological Protection), ICRP Publ. 14, Pergamon Press, London (1969).

2.21 International Commission on Radiological Protection,
Recommendations of the International Commission on Radiological
Protection (Adopted September 9, 1958), ICRP Publ. 1, p. 15, addendum
to para. (65), Pergamon Press, London (1959).

2.22 International Commission on Radiological Protection,
Recommendations of the International Commission on Radiological
Protection (Adopted September 17, 1965), ICRP Publ. 9, p. 15, para.
(87), Pergamon Press, London (1966).

3.0 DOSE ESTIMATION MODELS

Although the EXREM and INREM codes compute doses from several modes of exposure, only external exposure to the contaminated land surface (with model adaptations for calculating doses from beta emitters deposited on skin) and internal exposures resulting from intakes of contaminated food and beverages are considered here.

3.1 External Exposure to a Contaminated Landscape

The source is assumed to be a thin, infinite, smooth plane uniformly contaminated; air is the only shielding medium. The only rate process assumed to affect the concentration of fallout per unit area following deposition is radioactive decay; no loss due to environmental factors (e.g., runoff and erosion) is considered.

Crocker and Connors^{3.1} was the primary reference for radionuclide energies, abundances, and radioactive half-lives of fission products, whereas Crocker and Wong^{3.2} provided much of the data on induced activities. When the required data could not be found in these two references, the Table of Isotopes by Lederer et al.^{3.3} was used. In some cases, when data in Crocker and Connors or Crocker and Wong differed greatly from Lederer et al., the Lederer source was used because it is a more recent publication. Appendix I is a computer listing from the EXREM code of radionuclide index identification number, atomic number, name, decay constant, and the total number of beta particles and gamma photons emitted by each of 170 radionuclides for which external doses were estimated.

Fission product decay chains and branching ratios used in the EXREM code were taken from Fleming;^{3.4} however, no nuclide with a radioactive half-life of 10 minutes or less was included in the compilation if the nuclide was first in a decay chain. Lederer^{3.3} was the source for the few nonfission-product nuclides (^{188}W , ^{202}Pb , ^{210}Pb , ^{237}U , and ^{241}Pu) decaying to radioactive daughters of potential importance.

The gamma dose model in EXREM uses the linear absorption coefficient ($\mu - \sigma_s$) to account for the absorption of radiation in air. A table of $\mu - \sigma_s$ (derived from multiplying the mass absorption coefficient by the density of air) is stored in the code and necessary values are obtained by Lagrangian interpolation. The National Bureau of Standards Handbook No. 1003^{3.5} was the source of mass absorption coefficients. By using $\mu - \sigma_s$ to describe energy absorption in air, the original photon energy lost from the site of interaction by Compton scattering was excluded from consideration in the calculations. This will tend to produce a conservative estimate of dose.

3.1.1 Dose Rate

The dose rate at time t , including the contribution from radionuclide decay chains, is denoted by

$$R_{iq\ell}(t) = C_{i\ell}(t) D_{iq} \quad (3.1)$$

where i = radionuclide index,

q = radiation index (β for beta radiation; γ for gamma radiation),

ℓ = location index,

$C_{i\ell}(t)$ = areal concentration ($\mu\text{Ci}/\text{cm}^2$) of the i^{th} radionuclide at the ℓ^{th} location at time t ,

D_{iq} = dose rate factor ($\text{rem}/\mu\text{Ci-hr} \times \text{cm}^2$), and
 t = time (hours).

The basic dose rate factor for gamma radiation ($q = \gamma$) at the surface of a body immersed in air was adapted from Morgan and Emerson^{3.6} and is written

$$D_{i\gamma} = 827 B \sum_{n=1}^{N_{\gamma i}} \epsilon_{in} f_{in} \mu(\epsilon_{in}) E_1[\mu(\epsilon_{in})x] \quad (\text{rem/hr}), \quad (3.2)$$

where

$D_{i\gamma}$ = dose equivalent rate (rem/hr) from gamma photons at a height of x cm above a landsurface contaminated with $1 \mu\text{Ci}$ of radionuclide i per cm^2 ,

$B = 1.14$ = backscatter correction for a body immersed in air,

n = photon index,

$N_{\gamma i}$ = number of gamma photons emitted by the i^{th} radionuclide,

ϵ_{in} = energy (MeV) of the n^{th} photon emitted by the i^{th} radionuclide,

f_{in} = abundance (dimensionless) of the n^{th} photon emitted by the i^{th} radionuclide,

$\mu(\epsilon_{in}) = \mu - \sigma_s$ in the usual notation = linear absorption coefficient (cm^{-1}) for the n^{th} photon of the i^{th} radionuclide, and

$E_1[\mu(\epsilon_{in})x]$ = E-function of the first order for the argument $[\mu(\epsilon_{in})x]$.

When the radiation source is from beta emissions, the dose rate factor is computed from the following expression^{3.7}

$$R_{i\beta} = 1.07 \sum_{n=1}^{N_{\beta i}} \{ \nu \alpha (F[C, \nu, a(x)] + \exp[1 - \nu a(x)]) f_{in} \bar{E}_{in} \} \quad (3.3)$$

where $R_{i\beta}$ = dose equivalent rate (rem/hr) at a height of x cm above a
landsurface contaminated with $1 \mu\text{Ci}/\text{cm}^2$ of beta-emitting
radionuclide i ,

n = particle index,

$N_{\beta i}$ = number of beta particles emitted by the i^{th} radionuclide,

f_{in} = abundance (dimensionless) of the n^{th} beta particle emitted
by the i^{th} radionuclide,

$\bar{E}_{in}$ = average energy (MeV) of the n^{th} beta particle emitted by
the i^{th} radionuclide,

$$C = \begin{cases} 3.0, & E_{in} < 0.17, \\ 2.0, & 0.17 \leq E_{in} < 0.5, \\ 1.5, & 0.5 \leq E_{in} < 1.5, \\ 1.0, & 1.5 \leq E_{in}, \end{cases}$$

E_{in} = maximum energy (MeV) of the n^{th} beta particle emitted by the
 i^{th} radionuclide,

$$\alpha = \begin{cases} 0.190, & E_{in} < 0.17, \\ 0.260, & 0.17 \leq E_{in} < 0.5, \\ 0.297, & 0.5 \leq E_{in} < 1.5, \\ 0.333, & 1.5 \leq E_{in}, \end{cases}$$

$$v = \begin{cases} \frac{(18.6)}{(E_{\beta in} - 0.036)^{1.37}} & \text{if the radionuclide is not } ^{90}\text{Sr}, \\ \frac{(0.83)(18.6)}{(E_{\beta in} - 0.036)^{1.37}} & \text{if the radionuclide is } ^{90}\text{Sr}, \end{cases}$$

$$F[C, v, a(x)] = \begin{cases} C \left\{ 1 + \ln \left[\frac{C}{va(x)} \right] - \exp \left[1 - \left(\frac{va(x)}{C} \right) \right] \right\} & \text{if } va(x) < C, \\ 0 & \text{if } va(x) \geq C, \text{ and} \end{cases}$$

$a(x)$ = distance from the contaminated surface multiplied by the density of air (g/cm^2).

The areal concentration, $C_{il}(t)$, is derived from the nuclide chain equations for radioactive decay. For a single detonation, an explicit expression for the areal concentration at time t of the i^{th} radionuclide in a pathway for radioactive decay is denoted by

$$C_{il}(t) = \begin{cases} C_{il}^0 \exp(-\lambda_1 T), & i = 1 \\ C_{il}^0 \exp(-\lambda_i T) + T \sum_{k=1}^{i-1} \left[C_{kl}^0 \sum_{j=k}^{i-1} Y_{ij}(T) \lambda_{j+1} f_j \prod_{\substack{s=k \\ s \neq j}}^{i-1} \left(\frac{\lambda_{s+1} f_s}{\lambda_s - \lambda_j} \right) \right], & i > 1, \end{cases} \quad (3.4)$$

where

$$T = t - t_0,$$

$$\prod_{\substack{s=k \\ s \neq j}}^{i-1} \left(\frac{\lambda_{s+1} f_s}{\lambda_s - \lambda_j} \right) = 1 \quad \text{if } k=i-1,$$

$$Y_{ij}(T) = \left[\frac{\exp(-\lambda_j T) - \exp(-\lambda_i T)}{(\lambda_i - \lambda_j) T} \right],$$

λ_i = radiological decay constant (hours^{-1}) of the i^{th} radionuclide,

f_i = fraction of nuclei of the i^{th} radionuclide which decay to the $i+1^{\text{st}}$ nuclide in the pathway,

t_0 = time (hours) of environmental release,

$$C_{il}^0 = g_{il} Y_i,$$

g_{il} = location correction factor for the i^{th} radionuclide at the l^{th} location, and

Y_i = yield (μCi) released to the environment from the detonation.

To determine the areal concentration of a radionuclide in a chain containing more than one pathway for radioactive decay, contributions for the nuclide are summed for each pathway which is unique up to that radionuclide.^{3.8}

The areal concentration, $M C_{il}(t)$, at time t of the i^{th} radionuclide resulting from M detonations is obtained by evaluating Eq. (3.4) where

$$C_{il}^0 = M-1 C_{il}(\tau_M) + g_{ilM} Y_{iM},$$

and where

τ_M = time (hours) of the M^{th} detonation,

$T = t - \tau_M$,

$g_{ilM} = g_{il}$ for the M^{th} detonation,

$Y_{iM} = Y_i$ for the M^{th} detonation, and

$M-1 C_{il}(\tau_M)$ = the areal concentration at time τ_M of the i^{th} radionuclide resulting from the first $M-1$ detonations.

Although it is stated at the beginning of this chapter that the dose models apply to a plane source when the absorbing medium is air, these models also may be used to estimate beta dose rate (and cumulative beta dose) when the radioactive source is deposited on curved body surfaces provided the radius of curvature is larger than the maximum β -particle range.^{3.9} This condition is met for fallout radionuclides deposited directly on most of man's skin surface. The level of contamination ($\mu\text{Ci}/\text{cm}^2$) is assumed to be the same for skin and land surface. In this situation, the subject would be standing in the open (i.e., out from underneath a thatched roof or the forest canopy) while fallout is being deposited, and the exposed portions of his body would be covered by the same material and radioactivity level as was deposited

on the land at that location. The values used for $a(x)$ in Eq. (3.3), the distance from the contaminated surface multiplied by the density of air, were adjusted to include 100 cm of air + 0.1 cm of skin for exposure above the land surface and only 0.1 cm of skin for deposition of radioactivity on the skin. In preparing input data for the EXREM code, 0.1 cm of skin was considered equal to 83 cm of air in terms of the shielding of beta particles. The range of beta particles in a medium is essentially independent of the type of material and may be expressed as the thickness times the density (mg/cm^2).

3.1.2 Cumulative Dose

The estimate of cumulative external dose equivalents (rem), or total external dose, for exposure beginning at t_1 and ending at t_2 is given by

$$TD_{iql}(t_1, t_2) = R_{iql} \int_{t_1}^{t_2} C_{il}(t) dt \text{ (rem)}, \quad (3.5)$$

where the terms are defined as above.

3.2 Internal Exposure from Ingestion of Food and Drink

The dose models used in INREM are presented here in their final form, and the reader is referred to previous publications for more detail concerning these internal dose models.^{3.10, 3.11} Dose equivalents (rem) resulting from the ingestion of radioactivity programmed as continuous or intermittent intakes were computed for various body organs. The parameters in these dose models change as a function of age of the individual exposed during the time period covered by the dose integration.

3.2.1 All Organs Except the G.I. Tract

The model programmed for all organs except the G.I. tract is written

$$D_{in}(t_1, t_2, t_b) = 51 \int_{t_1}^{t_2} I_i[(t-t_b), t] f_{in}(t-t_b) \left\{ \int_t^{t_2} \frac{\epsilon_{in}(s-t_b)}{m_n(s-t_b)} \exp\left[-\int_{t-t_b}^{s-t_b} \lambda_{in}(\gamma) d\gamma\right] ds \right\} dt \quad (\text{rem}), \quad (3.6)$$

where

$D_{in}(t_1, t_2, t_b)$ = Cumulative dose equivalent (rem) received during the time interval t_1 to t_2 from the i^{th} radionuclide in the n^{th} organ resulting from intake during this time interval by an individual born at t_b ,

t_1 = time (days) of initial intake relative to time of reference detonation,

t_2 = time (days) at end of period of interest relative to time of reference detonation,

t_b = time (days) of birth relative to time of reference detonation,

t = time (days) after reference detonation,

s = time after intake relative to time of reference detonation,

$I_i(t)$ = intake ($\mu\text{Ci/day}$) of i^{th} radionuclide at t ,

$m_n(t)$ = mass (g) of the n^{th} organ at t ,

$f_{in}(t)$ = fractional absorption (dimensionless) of the i^{th} radionuclide in the n^{th} organ at t ,

$\epsilon_{in}(t)$ = effective absorbed energy (MeV) of the i^{th} radionuclide in the n^{th} organ at t , and

$\lambda_{in}(t)$ = effective elimination constant (days^{-1}) of the i^{th} radionuclide in the n^{th} organ for age γ at t .

This model is based on the assumption that radionuclides are taken into the body at the rate of $1 \mu\text{Ci/day}$ and that elimination from the reference organ is following a single exponential function (except for ^{90}Sr , in which case a three exponential retention function is used).

3.2.2 GI Tract

The model for estimating dose to the GI tract relates intake to dose received from intake at the $(\text{MPC})_a$ or $(\text{MPC})_w$. An advantage of this approach is that it utilizes the MPC for the critical segment of the GI tract, which already has built into it the time required for the intake to reach the critical segment, and the time required for emptying the segment. The model programmed for the G.I. Tract is written

$$D_{i\alpha}(t_1, t_2, t_b) = \frac{0.3/7}{A_n(\text{MPC})_{i\alpha}} \int_{t_1}^{t_2} I_i(t-t_b, t) P_k(t-t_b) Q_{i\alpha}(t-t_b) R_{i\alpha}(t-t_b) dt$$

(rem), (3.7)

where

$D_{i\alpha}(t_1, t_2, t_b)$ = Cumulative dose equivalent (rem) received by the critical segment of the GI tract during the time interval t_1 to t_2 from the i^{th} radionuclide in form α ($\alpha = 1$ for soluble, $\alpha = 2$ for insoluble) resulting from intake during this time interval by an individual born at t_b ,

t_1 = time (days) of initial intake relative to time of reference detonation,

t_2 = time (days) at end of period of interest relative to time of reference detonation,

t_b = time (days) of birth relative to time of reference detonation,

t = time (days) after reference detonation,

0.3/7 = maximum permissible dose rate (rem/day) to the critical segment of the GI tract for standard man,

A_n = intake (cm^3/day) of water by standard man
(n = index for standard man),

$(\text{MPC})_{i\alpha}$ = the maximum permissible concentration ($\mu\text{Ci}/\text{cm}^3$) of the i^{th} radionuclide of form α in water,

$I_i(t)$ = intake ($\mu\text{Ci}/\text{day}$) of i^{th} radionuclide at t ,

$P_k(t-t_b) = m_n/m_l$,

$Q_{i\alpha}(t-t_b) = \epsilon_{il\alpha}/\epsilon_{in\alpha}$,

$R_{i\alpha}(t-t_b) = f_{il\alpha}/f_{in\alpha}$, and where

m_l = mass (g) of the critical segment of the GI tract of an individual in the l^{th} age group,

$\epsilon_{il\alpha}$ = effective absorbed energy (MeV) of the i^{th} radionuclide of form α in the critical segment of the GI tract of an individual in the l^{th} age group, and

$f_{il\alpha}$ = fraction of the intake from ingestion of the i^{th} radionuclide of form α reaching the critical segment of the GI tract of an individual in the l^{th} age group.

3.3 Genetically Significant Dose

Genetic dose is considered both at the level of the individual and at the population level because separate radiation safety guides are available for each.^{3.12} In the present instance, genetic dose to an individual is determined on the basis of dose estimates computed with EXREM and INREM, supplemented with additional information to improve the estimation of potential gonadal dose. At the population level, genetically significant dose requires estimation. Genetically significant dose to a population is the dose which, if it were received by each person from conception to the mean age of childbearing, would result in the same genetic burden to the whole population as do the actual doses received by the individuals.^{3.13} Estimates of genetic doses to individuals are used in conjunction with demographic information to estimate genetically significant dose.

The formulation used to estimate genetically significant doses for populations is adapted from the 1958 Report of UNSCEAR.^{3.13} Genetically significant dose is given by

$$D^* = \frac{1}{wN} \sum_k d_k^* N_k^* w_k^* \quad (\text{rem}), \quad (3.8)$$

where

- * denotes the sex,
- k denotes the age group,
- D = genetically significant dose (rem),
- w = future number of children expected by an average individual,
- N = total number of individuals in the population, and
- d = gonadal dose (rem) to the individual.

References for Chapter 3.0

- 3.1 G. R. Crocker and M. A. Conners, Gamma-Emission Data for the Calculation of Exposure Rates from Nuclear Debris, Vol. I. Fission Products, USNRDL-TR-876 (June 10, 1965).
- 3.2 G. R. Crocker and D. T. Wong, Gamma-Emission Data for the Calculation of Exposure Rates from Nuclear Debris. Vol. II. Induced Activities, USNRDL-TR-888 (August 13, 1965).
- 3.3 C. M. Lederer, J. M. Hollander, and I. Perlman, Table of Isotopes, 6th Ed., John Wiley and Sons, Inc., New York, 1967.
- 3.4 E. H. Fleming, Jr., Fission Product Decay Chains, Vol. I, UCRL-50243 (March 31, 1967).
- 3.5 G. R. White, X-Ray Attenuation Coefficients from 10 KeV to 100 MeV, NBS Handbook 1003 (May 13, 1952).
- 3.6 K. Z. Morgan and L. C. Emerson, "Dose from External Sources of Radiation," p. 280 in Principles of Radiation Protection, ed. by K. Z. Morgan and J. E. Turner, John Wiley and Sons, Inc., New York, 1967.
- 3.7 R. Loevinger, E. M. Japha, and G. L. Brownell, "Discrete Radioisotope Sources," in Radiation Dosimetry, ed. by G. J. Hine and G. L. Brownell, Academic Press, New York, 1956.
- 3.8 W. Doyle Turner, The EXREM II Computer Code for Estimating External Doses to Populations from Construction of a Sea-Level Canal with Nuclear Explosives, CTC-8 (July 21, 1969).
- 3.9 W. D. Turner, S. V. Kaye, and P. S. Rohwer, EXREM and INREM Computer Codes for Estimating Radiation Doses to Populations from Construction of a Sea-Level Canal with Nuclear Explosives, K-1752 (September 16, 1968).

3.10 P. Loevinger, E. M. Japha, and G. L. Brownell, "Discrete Radioisotope Sources," p. 721 in Radiation Dosimetry, ed. by G. J. Hine and G. L. Brownell, Academic Press, New York, 1956.

3.11 S. V. Kaye and P. S. Rohwer, "Methods of Estimating Population Exposures from Plowshare Applications," in Proceedings of Symposium on Public Health Aspects of Peaceful Uses of Nuclear Explosives, SWRHL-82, Las Vegas, Nevada, April 7-11, 1969.

3.12 International Commission on Radiological Protection, Recommendations of the International Commission on Radiological Protection (Adopted Sept. 17, 1965), ICRP Publ. 9, Pergamon Press, London (1966).

3.13 United Nations, Report of the United Nations Scientific Committee on the Effects of Atomic Radiation, General Assembly Official Records: Thirteenth Session, Suppl. No. 17 (A/3838), New York (1958).

4.0 RADIATION DOSE ESTIMATES

All radiation dose estimates were computed with the EXREM and INREM codes on an IBM 360/75 computer. The nuclide-by-nuclide dose estimates were printed in conventional format but cannot be shown here because of classification restrictions. Since the estimated total doses are not classified, these are presented here. Photographs of computer-drawn Cathode Ray Tube (CRT) graphs of dose vs. time constitute the basic format for the display of estimated doses.

Dose estimates in this report are for dry deposition within the exclusion area; no input data were provided relative to wet deposition or deposition outside the exclusion areas.

4.1 Potential Exposures for Route 17

4.1.1 External Gamma Dose from Contaminated Land Surface

Graphs of potential external gamma dose (mrem) plotted as a function of reentry time are shown in Appendix II, Figs. 1-13, for locations 1-13 (names corresponding to locations 1-13 are indicated in the figure titles). Doses accumulated to 70 years after the initial detonation and the yearly dose rates are plotted on each CRT graph. The first point plotted on each graph represents 30 days after the last detonation (2.65 years after the first detonation), which is the earliest reentry time considered. Table 4.1 shows that for each location, at least 98 percent of the 70-year dose is accrued the first 3 years after the initial detonation (approximately one-half year after the last detonation). Consequently, only a small fraction of the estimated 70-year doses resulting from exposures beginning at the time of the first detonation are shown on the graphs in

Table 4.1. Partition of Potential External Gamma Dose
Between 0-3 Years and 3-70 Years after First Detonation

Location	Cumulative Dose (rem)			Percent of 70-year Dose Delivered by 3 years (%)
	0-3 Years	0-70 Years	3-70 Years	
1. San Miguel	6.42	6.49	0.0657	98.9
2. Punta Cocos	22.8	23.1	0.252	98.7
3. Garachine	27.8	28.3	0.456	98.2
4. Rio Congo	221.	224.	2.98	98.7
5. La Palma	205.	208.	3.01	98.6
6. Chepigana	5.08	5.21	0.129	97.5
7. Junction Rio Chucunaque & Rio Chiatí	6.06	6.10	0.0388	99.3
8. Uala	118.	120.	1.83	98.3
9. Yantupo	13.7	13.8	0.0954	99.3
10. Mulatupo	121.	122.	1.01	99.2
11. Acla	34.0	34.2	0.221	99.4
12. Sabalo	1.03	1.04	0.00730	99.0
13. Ailigandí	.966	0.993	0.00720	99.3

Appendix II. A great reduction in potential external dose could be realized if reentry is delayed long enough to allow for the decay of relatively short-lived radionuclides. These graphs show when reentry might be considered, depending on the dose considered acceptable. Reentry is discussed in more detail in Chapter 5.0.

The instantaneous dose rates (rem/hour) as a function of reentry time for all 13 locations are shown in Appendix III, Figs. 1-13. Dose rates below 10^{-6} rem/hour are plotted at 10^{-6} rem/hour (8.8 mrem/yr) for convenience in the CRT graphical output. These graphs indicate the potential dose rates that construction personnel might experience in the exclusion area. The "spikes" in these CRT plots correspond to the time of arrival of fallout from individual detonations. For example, location 1 receives fallout from 5 detonations while location 2 receives fallout from 13 detonations. The maximum dose rates (spikes) shown in the CRT plots may not reflect the real maxima because each peak corresponds to $H + 24$ (i.e., 24 hours after each detonation). The maximums probably would occur before $H + 24$, depending on the size of the explosive, the distance to locations of interest, and meteorological phenomena affecting the cloud; however, our input data included only the radioactivity deposited at all 13 locations after the first 24 hours. No data were provided on levels of contamination for times less than one day after the individual detonations. Furthermore, some of the radionuclides with short radioactive half-lives (minutes or hours) eliminated from our input data would tend to increase the peak dose rates.

4.1.2 External Beta Dose to Skin

Since the radionuclides making up our input data for each detonation are the same, and only the yield is assumed to differ for various detonations, an assessment of the potential external beta dose can be made by computing the ratio, β -dose/ γ -dose, for a single detonation. External beta dose estimates at a depth of 1 mm in human skin are presented in Fig. 4.1 as percent of total body gamma dose at 100 cm for two different levels of activity. These curves show that the size of the source term does not affect the magnitude of the percent. No values are plotted for the first day after detonation because the necessary input data were not available.

For the exposures represented in Fig. 4.1, the shapes of the dose curves are similar for the two different source terms; and the curves differ only slightly (1-4%) in dependence on the size of the source term as a function of time. All detonations would result in daily beta dose indexes falling within the approximate range indicated for the two source terms in Fig. 4.1. Additional features of this figure for these assumed exposure conditions are: 1) gamma exposure is always higher than beta dose; 2) beta dose to skin is always higher from deposition on skin than from deposition on land; and 3) daily beta dose index is not a constant, but rather a function of post-detonation time.

4.1.3 Internal Dose from Ingestion

Estimates of potential internal doses from ingestion of contaminated foods and beverages are presented in Appendix IV, Figs. 1-9. The estimated values are totals representing the dose from 31 radionuclides selected by BCL for detailed consideration. One figure is provided for each reference organ. Estimates of

Fig. 4.1. Evaluation of Potential Daily External Beta Dose to Human Skin.

potential internal dose are presented as a function of reentry time into watershed 5. Watershed 5 is only one of several watersheds which together embrace the entire proposed exclusion area; however, watershed 5 has the highest predicted fallout concentrations, and the greatest exposure potential for inhabitants upon reentry into the area. Once indigenous populations reenter watershed 5 following the completion of nuclear excavation, each individual is assumed to remain there for the balance of his lifetime. Each figure in Appendix IV contains two curves; one curve represents an estimate of maximum dose commitment (mrem), and the other, an estimate of maximum annual dose rate (mrem/year). Dose commitment is an estimate of the maximum internal dose an individual can receive due to radionuclides taken into the body (i.e., the dose already received plus the dose to be received in his remaining lifetime). The dose estimates presented in Appendix IV are considered as maximums because they are the highest potential doses estimated for ingestion. Food intake data used by BCL in estimating daily radionuclide ingestion for various age and ethnic groups (see section 2.5.5) are average values for individuals within the respective age ranges. In discussing the relationship between average and maximum doses in exposure situations such as this, the FRC suggests use of the arbitrary assumption that the majority of individuals do not vary from the average by a factor greater than three.^{4.1} If one adopts that assumption, and even if one has a high degree of confidence in the information used to obtain the dose estimates, one must recognize that some individuals within the age and ethnic group for which highest dose estimates have been obtained could be expected to receive doses which exceed that dose, by a factor of three.

Dose estimates were obtained for individuals representing 5 age groups (0-1, 1-5, 5-10, 10-15, and greater than 15 years of age) within each of four indigenous populations (Cuna Indians, Choco Indians, Negroes, and Colonists). In every case these dose estimates are no greater than those presented in Appendix IV. Emphasis is placed on estimates of maximum dose because, barring great differences in numbers of individuals and/or radiation sensitivities among groups within the populations, protection of the group with the highest potential dose should adequately protect all groups. The range of estimated dose commitments for total body and bone of all age and ethnic groups is illustrated in Figs. 1-8 of Appendix V. The magnitude of estimated dose commitment and annual dose rate to an organ varies among populations and among age groups within the population. Interpopulation variations shown for a given age group and reference organ are attributable to dietary differences because daily radionuclide intake was the only parameter used to differentiate the four populations. Intrapopulation variations, on the other hand, reflect the influences of the five parameters used to differentiate age groups. The figures in Appendix V are limited to the first few years following the completion of nuclear excavation because the differences for later reentry times are negligible. Similar variations of estimated dose commitments among populations and among age groups within populations were observed for other reference organs. Similar ranges among values were also observed in the estimates of annual dose; however, the estimated annual dose rates for most reference organs decline to less than 10 mrem/year soon after the last detonation, and the significance of observed differences beyond that point is questionable.

4.1.4 Summation of External and Internal Dose Estimates

Estimation of total dose for a given radiation exposure situation requires a dose estimate for each mode of potential exposure. In this study, total dose estimates were obtained by adding the external dose estimates for location 4 (Rio Congo) to the internal dose estimates for watershed 5. The external dose estimates for Rio Congo were used for two reasons: 1) Rio Congo is located in watershed 5, and more important, 2) the initial areal fallout concentration at Rio Congo is approximately equal to the average initial fallout concentration in watershed 5.

Tables 4.2-4.4 demonstrate the addition of potential external and internal doses for three reentry times. Presentation of these data for three reentry times illustrates the relative importance of exposure modes as a function of reentry time. Although external dose was dominant at all post-evacuation times, that dominance increases for later reentry times. One probable explanation for this increasing dominance of external dose is the fact that radioactive decay was the only parameter considered as reducing the external exposure as a function of time. This addition of potential external and internal doses tends to deemphasize age and ethnic group differences because the external dose estimates, which dominate here, were not calculated with models reflecting age and population variations. To illustrate the trend of summed dose throughout the post-excitation period, summed dose estimates for one reference organ (total body) are presented in Fig. 4.2 for reentry times up to 50 years after the first detonation.

Table 4.2. Summation of Dose Estimates for Modes of Exposure Considered, Watershed 5, Route 17.
Exposure starting 2.652 years after the first detonation (30 days after the last detonation).

Body Organ	Critical Population	Critical Age Group (years)	Estimated Dose (rem) to Age 70 years (Internal + External)	Estimated Maximum Annual Dose Rate (rem/year) (Internal + External)
Total Body	Colonist	1-5	$1.00 + 4.25 = 5.25$	$0.968 + 1.96 = 2.93$
Bone	Negro	0-1	$5.75 + 4.25 = 10.0$	$5.21 + 1.96 = 7.17$
Liver	Colonist	1-5	$1.27 + 4.25 = 5.52$	$1.17 + 1.96 = 3.13$
Kidneys	Colonist	1-5	$4.17 + 4.25 = 8.42$	$3.97 + 1.96 = 5.93$
Thyroid	Colonist	1-5	$5.37 + 4.25 = 9.62$	$5.34 + 1.96 = 7.30$
Testes	Colonist	1-5	$1.15 + 4.25 = 5.40$	$1.12 + 1.96 = 3.08$
Ovaries	Colonist	1-5	$1.00 + 4.25 = 5.25$	$0.968 + 1.96 = 2.93$
Lungs	Colonist	1-5	$1.00 + 4.25 = 5.25$	$0.968 + 1.96 = 2.93$
GI Tract	Colonist	1-5	$1.04 + 4.25 = 5.29$	$1.01 + 1.96 = 2.97$

Table 4.3. Summation of Dose Estimates for Modes of Exposure Considered, Watershed 5, Route 17.
Exposure Starting 5 years after the first detonation.

Body Organ	Critical Population	Critical Age Group (years)	Estimated Dose (rem) to Age 70 years (Internal + External)	Estimated Maximum Annual Dose Rate (rem/year) (Internal + External)
Total Body	Colonist	0-1	$0.0254 + 1.72 = 1.74$	$0.00238 + 0.203 = 0.205$
Bone	Colonist	0-1	$0.332 + 1.72 = 2.05$	$0.0229 + 0.203 = 0.226$
Liver	Colonist	0-1	$0.0309 + 1.72 = 1.75$	$0.00252 + 0.203 = 0.206$
Kidneys	Negro	0-1	$0.0381 + 1.72 = 1.76$	$0.00402 + 0.203 = 0.207$
Thyroid	Colonist	0-1	$0.0255 + 1.72 = 1.74$	$0.00239 + 0.203 = 0.205$
Testes	Colonist	0-1	$0.0258 + 1.72 = 1.74$	$0.00245 + 0.203 = 0.205$
Ovaries	Colonist	0-1	$0.0254 + 1.72 = 1.74$	$0.00238 + 0.203 = 0.205$
Lungs	Colonist	0-1	$0.0254 + 1.72 = 1.74$	$0.00238 + 0.203 = 0.205$
GI Tract	Negro	0-1	$0.0760 + 1.72 = 1.80$	$0.0269 + 0.203 = 0.230$

Table 4.4 • Summation of Dose Estimates for Modes of Exposure Considered, Watershed 5, Route 17.
Exposure starting 30 years after the first detonation.

Body Organ	Estimated Dose (rem) to Age 70 years (Internal + External)	Estimated Maximum Annual Dose Rate (rem/year) (Internal + External)
Total Body	$0.0154 + 0.610 = 0.625$	$0.00194 + 0.0198 = 0.0217$
Bone	$0.165 + 0.610 = 0.775$	$0.0123 + 0.0198 = 0.0321$
Liver	$0.0176 + 0.610 = 0.628$	$0.00193 + 0.0198 = 0.0217$
Kidneys	$0.0209 + 0.610 = 0.631$	$0.00200 + 0.0198 = 0.0218$
Thyroid	$0.0154 + 0.610 = 0.625$	$0.00194 + 0.0198 = 0.0217$
Testes	$0.0161 + 0.610 = 0.626$	$0.00196 + 0.0198 = 0.0217$
Ovaries	$0.0154 + 0.610 = 0.625$	$0.00194 + 0.0198 = 0.0217$
Lungs	$0.0154 + 0.610 = 0.625$	$0.00194 + 0.0198 = 0.0217$
GI Tract	$0.0345 + 0.610 = 0.644$	$0.00431 + 0.0198 = 0.0241$

Fig. 4.2. Total Estimated Dose to the Total Body for Reentry Times up to 50 Years after the First Detonation, Watershed 5, Route 17.

4.2 Potential Exposures for Route 25

4.2.1 Internal Dose from Ingestion

Estimates of potential internal dose from ingestion of contaminated foods and beverages are presented in Appendix VI, Figs. 1-9. Due to the marked similarities to the hypothetical exposure situations and dose estimates for Route 17, description of the results for Route 25 will be simplified; the reader may refer back to Section 4.1.3. These internal estimates are for watershed 2, one of several which together embrace the entire proposed exclusion area for Route 25. Daily radionuclide intake (as a function of diet) is the only internal dose parameter used to differentiate the two routes; the same four ethnic groups are assumed to be indigenous to each route. The range of variation in potential dose commitment among all age and ethnic groups is illustrated by the examples for total body and bone in Figs. 1-8 of Appendix VII.

4.2.2 Summation of External and Internal Dose Estimates

Infinite gamma exposure contour maps provided by ESSA indicate that the highest contour passing through watershed 2 is 10 R/70 years for exposures beginning 30 days after the last detonation; therefore, we used 10 rems as an estimate of external gamma dose resulting from 70 years of exposure to contaminated land surface. Time course for the delivery of external dose was assumed to be identical with that for Route 17.

The additions of external and internal dose estimates for various reentry times are shown in Tables 4.5-4.7. Again we emphasize that these summed estimated doses do not include all potential exposure modes. As in the case of Route 17, the doses resulting from external exposure to the contaminated land surface are the dominant ones.

Table 4.5. Summation of Dose Estimates for Modes of Exposure Considered, Watershed 2, Route 25.
Exposure starting 1.570 years after the first detonation (30 days after the last detonation).

Body Organ	Critical Population	Critical Age Group (years)	Estimated Dose (rem) to Age 70 years (Internal + External)	Estimated Maximum Annual Dose Rate (rem/year) (Internal + External)
Total Body	Colonist	1-5	0.560 + 10.0 = 10.6	0.556 + 4.61 = 5.17
Bone	Choco	1-5	1.58 + 10.0 = 11.6	1.41 + 4.61 = 6.02
Liver	Choco	1-5	0.905 + 10.0 = 10.9	0.885 + 4.61 = 5.50
Kidneys	Choco	1-5	5.82 + 10.0 = 15.8	5.74 + 4.61 = 10.4
Thyroid	Colonist	1-5	0.942 + 10.0 = 11.0	0.938 + 4.61 = 5.55
Testes	Colonist	1-5	0.569 + 10.0 = 10.6	0.564 + 4.61 = 5.17
Ovaries	Colonist	1-5	0.560 + 10.0 = 10.6	0.556 + 4.61 = 5.17
Lungs	Colonist	1-5	0.560 + 10.0 = 10.6	0.556 + 4.61 = 5.17
GI Tract	Choco	1-5	0.582 + 10.0 = 10.6	0.563 + 4.61 = 5.17

Table 4.6. Summation of Dose Estimates for Modes of Exposure Considered, Watershed 2, Route 25.
Exposure starting 5 years after the first detonation.

Body Organ	Critical Population	Critical Age Group (years)	Estimated Dose (rem) to Age 70 years (Internal + External)	Estimated Maximum Annual Dose Rate (rem/year) (Internal + External)
Total Body	Cuna	0-1	0.00269 + 3.57 = 3.57	< 0.001 + 0.306 = 0.306
Bone	Cuna	0-1	0.129 + 3.57 = 3.70	0.0037 + 0.306 = 0.310
Liver	Cuna	> 15	0.0105 + 3.57 = 3.58	< 0.001 + 0.306 = 0.306
Kidneys	Cuna	> 15	0.020 + 3.57 = 3.59	0.001 + 0.306 = 0.307
Thyroid	Cuna	0-1	0.00269 + 3.57 = 3.57	< 0.001 + 0.306 = 0.306
Testes	Cuna	0-1	0.00269 + 3.57 = 3.57	< 0.001 + 0.306 = 0.306
Ovaries	Cuna	0-1	0.00269 + 3.57 = 3.57	< 0.001 + 0.306 = 0.306
Lungs	Cuna	0-1	0.00269 + 3.57 = 3.57	< 0.001 + 0.306 = 0.306
GI Tract	Cuna & Negro	0-1	0.00606 + 3.57 = 3.58	0.0014 + 0.306 = 0.307

Table 4.7. Summation of Dose Estimates for Modes of Exposure Considered, Watershed 2, Route 25.
Exposure starting 30 years after the first detonation.

Body Organ	Estimated Dose (rem) to Age 70 years (Internal + External)	Estimated Maximum Annual Dose Rate (rem/year) (Internal + External)
Total Body	$0.00114 + 1.44 = 1.44$	$< 0.001 + 0.047 = 0.047$
Bone	$0.0514 + 1.44 = 1.49$	$0.0023 + 0.047 = 0.049$
Liver	$0.00418 + 1.44 = 1.44$	$< 0.001 + 0.047 = 0.047$
Kidneys	$0.00602 + 1.44 = 1.45$	$< 0.001 + 0.047 = 0.047$
Thyroid	$0.00114 + 1.44 = 1.44$	$< 0.001 + 0.047 = 0.047$
Testes	$0.00114 + 1.44 = 1.44$	$< 0.001 + 0.047 = 0.047$
Ovaries	$0.00114 + 1.44 = 1.44$	$< 0.001 + 0.047 = 0.047$
Lungs	$0.00114 + 1.44 = 1.44$	$< 0.001 + 0.047 = 0.047$
GI Tract	$0.00256 + 1.44 = 1.44$	$< 0.001 + 0.047 = 0.047$

Other statements made in reference to Route 17 (see section 4.1.4) are also applicable here. Figure 4.3 shows the total estimated dose to total body as a function of reentry time for a period extending to 50 years after the first detonation.

4.3 Limitations of These Dose Estimates

None of the estimates of potential doses in this report has considered possible exposures from 1) the nonreleased (i.e., initially) radioactivity produced by the nuclear explosives, and 2) the released radioactivity that is not deposited locally, but which enters the stratosphere and becomes a part of world-wide fallout. Acceptable days for the detonations could be selected so that conditions are favorable for limiting the height of the main cloud to approximately 40,000 feet for the large detonations, avoiding the stratosphere which lies at approximately 55,000 feet in the equatorial zone. There is no similar procedure that can be followed to reduce or confine the nonreleased radioactivity in the excavation, other than to design explosives that produce less radioactivity. Behavior of the nonreleased radioactivity left in the crater is a matter of conjecture, particularly when water flows through the finished canal. In our opinion, considerable uncertainty exists in any predictions of the fate and effects of radioactivity from this source on man. However, BCL has indicated that their marine internal dose estimates include this nonreleased radioactivity.

Dose estimates can be no better than the input data used to compute them. Ideally, each dose estimate should be accompanied by some confidence limit and, where this is not possible or practicable, there should be some indication as to whether the dose estimates are conservative

Fig. 4.3. Total Estimated Dose to the Total Body for Reentry Times up to 50 Years after the First Detonation, Watershed 2, Route 25.

(assumptions used maximize the dose) or nonconservative (assumptions used do not maximize the dose). Because of uncertainties in the various input data in this study (including the source term) there is no basis on which to qualify these dose estimates; anything said would be speculation.

The areal deposition ($\mu\text{Ci}/\text{cm}^2$) of fallout radionuclides was forecast by assuming a released fraction, dispersal of the "cloud," and dry deposition rates. Any of these assumptions could be in error by a considerable margin. Any errors in predicting the fallout deposition of radionuclides are carried on through to the final dose estimates.

4.3.1 External Dose

Our estimates of external dose are limited to gamma total-body exposures from a radioactively contaminated land surface, and an ancillary evaluation of beta dose to human skin from external beta sources. External exposures might also be possible from submersion in the radioactive "cloud" (either before deposition or later as a result of resuspension of deposited radioactivity) or from submersion in contaminated water. Inclusion of these additional modes of exposure would probably result in some increase in external dose estimates.

Although each radionuclide produced by the nuclear detonations was not considered in this estimation of external dose, care was taken to include all important radionuclides. Some radionuclides, for which production data were provided, could not be included in our dose evaluations because the gamma spectra were not adequately described in the literature. Omission of these radionuclides is not significant because the quantities produced are relatively small.

A great deal of conservatism is built into the estimates of external dose because radioactive decay was the only process considered to alter the concentration on the land surface following deposition. Environmental half-times of the radionuclides were not available, although EXREM can handle such input as part of the nuclide decay chain equations. Almost all dose estimates of exposures during the detonation period, and for six months after the last detonation, would be due to radionuclides of relatively short half-lives. Probably no appreciable over-estimate of dose results from neglecting environmental half-times during this period, if the effective half-time were approximately equal to the radioactive half-life ($T_r = T = \frac{T_e T_r}{T_e + T_r}$, here T_r is radioactive half-life, T is effective half-time, and T_e is environmental half-time). For periods beginning three years after the first detonation, the largest fraction of potential dose would be contributed by exposures to radionuclides with long radioactive half-lives. If the environmental half-times were relatively short compared to the radioactive half-lives, for the radionuclides contributing to dose, then the environmental half-time would be the limiting parameter.

For any dose integration period, what is the magnitude of conservatism of a dose estimate calculated with $T = T_r$ vs. a dose estimate calculated with $T = \frac{T_e T_r}{T_e + T_r}$? If $F(t)$ represents the magnitude of conservatism of an estimated dose for a specified time period due to consideration of radioactive half-life only, then

$$F(t) = \frac{D_{T_r}(t)}{D_T(t)}, \quad (4.1)$$

where $D_{T_r}(t)$ = cumulative external dose calculated with radioactivity loss due only to radioactive decay, and
 $D_T(t)$ = cumulative external dose calculated with radioactivity losses due to environmental factors and radioactive decay.

Substituting a simple integral expression (assuming no input from parent radionuclides) for $D_{T_r}(t)$ and $D_T(t)$, we get

$$F(t) = \frac{k \int_0^t e^{-\lambda_r t} dt}{k \int_0^t e^{-\lambda t} dt}, \quad (4.2)$$

where k represents all constant terms necessary to compute dose.

Solution of Eqn. (4.2) gives

$$F(t) = \frac{T_r (1 - e^{-\lambda_r t})}{T (1 - e^{-\lambda t})}, \quad (4.3)$$

an equation for estimating the magnitude of conservatism due to exclusion of environmental half-times in dose computations. The utility of Eqn. (4.3) is explicit in the family of curves plotted in Fig. 4.4 for ratios of T_r/T as large as 100/1.

The following is a hypothetical example of how Fig. 4.4 can be used. Assume that 60 percent of the external gamma exposure from 20 to 70 years after the first detonation is due to a single radionuclide. When environmental processes are considered which might

Fig. 4.4. Graph of Conservatism Factors for Correcting External Dose Estimates that Utilize Radioactive Decay as the Only Process to Reduce the Radiation Field.

hasten the loss of this radionuclide from the land surface (exclusive of radioactive decay), the ratio T_R/T is found to be as high as 90. Dose estimates using only the radioactive half-life would be conservative by a factor of approximately 25 (see Fig. 4.4). Since this radionuclide in this example, contributes 60 percent of the external exposure for the period 20 years to 70 years after the first detonation, then the total dose estimated for all radionuclides during this period would be conservative by a factor of $25 \times 0.6 = 15$. This example shows how it might be possible to reduce the estimates of potential external dose if the required data on environmental half-times were available from field experiments in Panama and Colombia. If the ratio of T_R/T were taken to be only 30, then the conservatism factor would be 13 for the example radionuclide. Thus, a reduction T_R/T by a factor of 3 reduces the conservatism by only a factor of 2, indicating that the environmental half-time need not be known accurately.

Continuous external exposure was assumed for calculating the estimates of potential external dose in this study. If this daily exposure time were reduced to 12 or 8 hours per day, the estimates of total dose would be reduced proportionately by a factor of 2 or 3. Such a reduction might not be realistic in all cases because many natives spend a considerable amount of time out of doors, many houses do not have walls to provide radiation shielding, and many of the local building materials have little value as radiation shielding. Therefore, better estimates of daily exposure times of these populations may not be as important as estimates of the environmental half-times of radionuclides on the land surface.

4.3.2 Internal Dose

Internal dose has been estimated only for ingestion of contaminated foods and beverages. While ingestion would probably be the internal exposure mode of primary importance for this feasibility study, other modes of internal exposure have too much potential importance to be ignored. Inhalation exposure could become very important if the exclusion area were violated by members of the indigenous populations, or a "cloud" of vented radioactivity were to take an unexpected course over a populated area. We do not have adequate dose estimates with which to evaluate the potential seriousness of such eventualities.

Detailed internal dose estimates for each route were limited to 31 radionuclides which have the greatest dose potentials. This is based on all exposures starting no less than 30 days after the last detonation.

We attempted to identify critical segments within the four ethnic populations in our estimations of potential dose. Age-dependent parameters in our dose models, however, were evaluated largely on the basis of data drawn from Caucasian populations quite different from those living along the two proposed canal routes. In addition, the paucity of pertinent anatomical, physiological, and metabolic data has forced us in some cases to apply adult dosimetry parameters to all age groups, including children.

Reference for Chapter 4.0

4.1 Federal Radiation Council, Background Material for the Development of Radiation Protection Standards, Report No. 1, U.S. Govt. Ptg. Off., Wash., D.C. (May 1960).

5.0 COMPARISON OF DOSE ESTIMATES WITH RADIATION SAFETY CRITERIA^a

The radiation safety criteria used for this study have been reported previously,^{5.1} following the lead of recognized radiation protection authorities.^b The basic recommendations of these authorities apply to radiation doses from all sources other than natural background and medical sources. Our radiation safety criteria for this study were originally proposed on the assumption that the dose estimates to which these criteria might apply would include dose estimates for each radionuclide and each exposure pathway. That is to say, it was assumed that a rather detailed assessment would be made of all potential exposure situations, more or less as they might be expected to occur in the "real" world, simulating or constructing these exposure situations with real information or educated assumptions. As events have developed, this radiological safety assessment does not meet that standard, but it may be adequate for purposes of a feasibility study.

The estimates of potential internal doses are based on a systems analysis prediction of radionuclide concentrations in dietary items using the mean areal fallout concentration ($\mu\text{Ci}/\text{cm}^2$) in a reference watershed (watershed 5 for Route 17, and watershed 2 for Route 25) as the input data. Internal dose estimates for other watersheds are obtained by applying factors based on areal fallout concentrations, relying on the premise that all watersheds are identical in all

^aThis term is adopted to avoid any confusion with terms used by recognized authorities to designate their official guides.

^bThe recognized authorities include the International Commission on Radiological Protection (ICRP), the International Atomic Energy Agency (IAEA), the National Council on Radiation Protection and Measurements (NCRP), the Federal Radiation Council (FRC), and the British Medical Research Council (MRC).

parameters influencing internal dose other than the average initial areal fallout concentration. Such a simplification of the canal environment and an assumed behavior of radionuclides in food-chain pathways can hardly be expected to simulate the actual situation.

The estimates of potential internal doses used in these comparisons are the highest ones estimated for any of the considered ethnic or age groups living near the proposed canal alignments.

5.1 Assessment^c of the Potential Doses Estimated for Various Times of Reentry to Watershed 5, Route 17

Estimated doses assessed here include the contributions from external exposure to the contaminated land surface and from internal exposure via ingestion of contaminated foods and beverages. Assessment of the estimated dose for a given organ is obtained by a simple comparison with the appropriate radiation safety criteria. Following a procedure for handling multiple organ exposures suggested by the ICRP, if three or more organs each could receive more than one-half their respective maximum permissible doses (criteria), the exposure was regarded as one which would result in a dose exceeding the criteria.^{5.2}

All assessments are tabulated as functions of exclusion area reentry time (actually the assumed time of reentry to watershed 5). Reentry to other watersheds within the exclusion area might be possible at earlier times because the average initial fallout concentrations are lower in all other watersheds (see Table 2.3).

^c Assessment as used in this report has the following specific meaning: $\text{Assessment} = \text{dose estimate} \div \text{criterion}$.

We do not believe an assessment of less than 1.0 for any particular comparison necessarily indicates radiological safety feasibility. As we stated before, even if one had a high degree of confidence in these dose estimates and their corresponding assessments, further judgments and adjustments will need to be considered so that not all of each criterion is "used up" by this one exposure situation, i.e., excavation with nuclear explosives.

5.1.1 Maximum Annual Doses

Assessments pertaining to estimates of average annual dose to critical population groups for various assumed times of reentry to watershed 5 are listed in Table 5.1. Children ranging up to 5 years old constitute the critical population group in most of these assessments. No clear dependence of dose upon ethnic background is apparent from the dose estimates obtained in this study.

Since the ICRP does not provide guidance on the apportionment of somatic dose, this matter should probably be considered at the national level. Even without apportionment, it can be seen from the assessments listed in Table 5.1 that the criteria for total body and gonads might still be exceeded 5 years after the first detonation. Ten years after the first detonation, multiple organ exposures should not be excessive, and all assessments would be less than 0.5, suggesting that reentry to watershed 5 may be possible at that time. Since the input data ($\mu\text{Ci}/\text{cm}^2$) used for these dose estimates are averages for the watershed based on fallout contours that vary by orders of magnitude over the watershed, some parts of this watershed (and other watersheds) probably could be reentered earlier, while other areas may not be safe for longer than

Table 5.1. Assessments of Estimated Average Annual Doses to Critical Population Groups for Various Assumed Times of Reentry to Watershed 5, Route 17.
Assessment = dose estimate $\div$ criterion.

Body Organ	Radiation ^a Safety Criteria (rems/year)	Assessments Coincident with Various Reentry Times									
		30 Days After Last ^b Detonation	60 Days After Last ^b Detonation	3 Years After First Detonation	5 Years After First Detonation	10 Years After First Detonation	15 Years After First Detonation	20 Years After First Detonation	30 Years After First Detonation	40 Years After First Detonation	50 Years After First Detonation
Total Body	0.170	17.	11.	5.5	1.2	0.30	0.19	0.16	0.13	0.11	0.087
Bone	1.00	7.2	5.4	1.9	0.23	0.063	0.043	0.037	0.032	0.029	0.015
Liver	0.500	6.3	4.1	2.0	0.41	0.10	0.065	0.053	0.043	0.038	0.030
Kidneys	0.500	12.	7.8	2.8	0.41	0.10	0.065	0.053	0.044	0.038	0.030
Thyroid	0.500	15.	6.9	1.9	0.41	0.10	0.065	0.053	0.043	0.038	0.030
Testes	0.170	18.	12.	5.5	1.2	0.30	0.19	0.16	0.13	0.11	0.087
Ovaries	0.170	17.	11.	5.5	1.2	0.30	0.19	0.16	0.13	0.11	0.087
Lungs	0.500	5.9	3.9	1.9	0.41	0.10	0.065	0.053	0.043	0.038	0.030
GI Tract	0.500	5.9	4.2	2.6	0.46	0.11	0.071	0.058	0.048	0.042	0.030

^aK. E. Cowner, S. V. Kaye, P. S. Rohwer, W. S. Snyder, and E. G. Struxness, Dose-Estimation Studies Related to Proposed Construction of an Atlantic-Pacific Interoceanic Canal with Nuclear Explosives: Phase I, ORNL-4101, Table 7.5, Column 2 (March 1967).

^bLast detonation is 2.57 years after the first detonation.

10 years. Generally speaking, predicted fallout concentrations decrease as one moves away from the proposed canal alignment, suggesting that outer areas of the exclusion area could be reentered first. There are, however, factors other than radiation to be considered.

5.1.2 Genetically Significant Doses

The ICRP states that genetic dose should not exceed 5 rems/30 years for all sources excluding the dose from natural background radiation and from medical procedures.^{5.3} No special evaluations are required to apply this criterion to assessments of genetically significant dose in Table 5.2. If an assessment of 0.5 is acceptable (see section 2.7.3), then reentry could take place as early as 3 years after the first detonation. This assessment indicates that somatic dose (Table 5.1) would be more limiting than genetic dose.

5.2 Assessment of the Potential Doses Estimated for Various Times of Reentry to Watershed 2, Route 25

Assessments for watershed 2, Route 25, are similar to those for watershed 5, Route 17 (i.e., dose estimates are for the same exposure modes, identical assessment procedures are used, and the assessment results are similar). Because the assessments for the two routes were parallel, all discussions relative to Route 17 (see section 5.1) are applicable for Route 25 also, and the reader is referred to that section for details.

Table 5.2. Assessments of Estimated Genetically Significant Doses to Critical Population Groups for Various Assumed Times of Reentry to Watershed 5, Route 17.
Assessment = dose estimate + criterion.

Reentry Times	Radiation ^a Safety Criteria (rems / 30 Years)	Assessments for the Various Populations			
		Cuna Indians	Choco Indians	Negroes	Colonists
30 days after last ^b detonation	5	0.73	0.78	0.77	0.79
60 days after last ^b detonation	5	0.61	0.64	0.64	0.64
3 years after first detonation	5	0.45	0.46	0.46	0.46
5 years after first detonation	5	0.21	0.21	0.22	0.22
10 years after first detonation	5	0.12	0.12	0.12	0.12
15 years after first detonation	5	0.097	0.097	0.097	0.097
20 years after first detonation	5	0.086	0.086	0.086	0.086
30 years after first detonation	5	0.075	0.075	0.075	0.075
40 years after first detonation	5	0.065	0.065	0.065	0.065
50 years after first detonation	5	0.048	0.048	0.048	0.048

^aK. E. Cowser, S. V. Kaya, P. B. Rohwer, W. S. Snyder, and E. G. Struxness, Dose-Estimation Studies Related to Proposed Construction of an Atlantic-Pacific Interoceanic Canal with Nuclear Explosives: Phase I, ORNL-4101, p. 89 (March 1967).

^bLast detonation is 2.57 years after the first detonation.

5.2.1 Maximum Annual Doses

Assessments of estimated average annual doses are presented in Table 5.3 for age and ethnic groups receiving the highest estimated doses. In most cases, that group was between 0 and 5 years of age and there was no consistent pattern relative to ethnic background. Reentry, on the basis of somatic dose assessments, may be possible less than 10 years after the first detonation.

5.2.2 Genetically Significant Doses

Assessments of genetically significant dose for each of our ethnic groups for various assumed times of reentry to watershed 2 are listed in Table 5.4. If an assessment of 0.5 is acceptable, the values presented in Table 5.4 suggest that reentry could take place less than 5 years after the first detonation. As was the case for Route 17, genetic dose limitations appear to be less restrictive than those for somatic dose.

Table 5.5. Assessments of Estimated Average Annual Doses to Critical Population Groups for Various Assumed Times of Reentry to Watershed 2, Route 25.
Assessment = dose estimate $\div$ criterion.

Body Organ	Radiation ^a Safety Criteria (rems / year)	Assessment Coincident with Various Reentry Times									
		30 Days After Last ^b Detonation	60 Days After Last ^b Detonation	2 Years After First Detonation	5 Years After First Detonation	10 Years After First Detonation	15 Years After First Detonation	20 Years After First Detonation	30 Years After First Detonation	40 Years After First Detonation	50 Years After First Detonation
Total Body	0.170	30.	23.	13.	1.8	0.68	0.42	0.34	0.28	0.24	0.20
Bone	1.00	6.0	4.2	2.1	0.31	0.12	0.074	0.060	0.049	0.042	0.035
Liver	0.500	11.	8.1	4.3	0.61	0.23	0.14	0.11	0.094	0.080	0.070
Kidneys	0.500	21.	14.	5.0	0.61	0.23	0.14	0.11	0.094	0.080	0.070
Thyroid	0.500	11.	7.9	4.2	0.61	0.23	0.14	0.11	0.094	0.080	0.070
Testes	0.170	30.	23.	13.	1.8	0.68	0.42	0.34	0.28	0.24	0.20
Ovaries	0.170	30.	23.	13.	1.8	0.68	0.42	0.34	0.28	0.24	0.20
Lungs	0.500	10.	7.6	4.2	0.61	0.23	0.14	0.11	0.094	0.080	0.070
GI Tract	0.500	10.	7.8	4.4	0.61	0.23	0.14	0.11	0.094	0.080	0.070

^aK. L. Cowser, S. V. Kaye, P. S. Rohwer, W. S. Snyder, and E. O. Struxness, Dose-Estimation Studies Related to Proposed Construction of an Atlantic-Pacific Interoceanic Canal with Nuclear Explosives: Phase I, ORNL-4101, Table 7.5, Column 2 (March 1967).

^bLast detonation is 1.49 years after the first detonation.

Table 5.4. Assessments of Estimated Genetically Significant Doses to Critical Population Groups for Various Assumed Times of Reentry to Watershed 2, Route 25.
Assessment = dose estimate + criterion.

Reentry Times	Radiation ^a Safety Criteria (rems / 30 Years)	Assessments for the Various Populations			
		Cuna Indians	Choco Indians	Negroes	Colonists
30 days after last ^b detonation	5	1.67	1.73	1.72	1.72
60 days after last ^b detonation	5	1.42	1.45	1.45	1.45
2 years after first detonation	5	1.05	1.06	1.08	1.06
5 years after first detonation	5	0.40	0.40	0.41	0.41
10 years after first detonation	5	0.27	0.28	0.28	0.28
15 years after first detonation	5	0.23	0.23	0.23	0.23
20 years after first detonation	5	0.20	0.20	0.20	0.20
30 years after first detonation	5	0.17	0.17	0.17	0.17
40 years after first detonation	5	0.15	0.15	0.15	0.15
50 years after first detonation	5	0.11	0.11	0.11	0.11

^aK. E. Cowser, S. V. Kaye, P. S. Rohwer, W. S. Snyder, and E. G. Struxness, Dose-Estimation Studies Related to Proposed Construction of an Atlantic-Pacific Interoceanic Canal with Nuclear Explosives: Phase I, ORNL-4101, p. 89 (March 1967).

^bLast detonation is 1.49 years after the first detonation.

References for Chapter 5.0

5.1 K. E. Cowser, S. V. Kaye, P. S. Rohwer, W. S. Snyder, and E. G. Struxness, Dose Estimation Studies Related to Proposed Construction of an Atlantic-Pacific Interoceanic Canal with Nuclear Explosives: Phase I, ORNL-4101 (March, 1967).

5.2 International Commission on Radiological Protection, Recommendations of the International Commission on Radiological Protection (Adopted Sept. 17, 1965), ICRP Publ. 9, p. 12, Pergamon Press, London (1966).

5.3 International Commission on Radiological Protection, Recommendations of the International Commission on Radiological Protection (Adopted Sept. 9, 1958), ICRP Publ. 1, p. 15, para. 64, Pergamon Press, London (1959).

6.0 CONCLUSIONS AND RECOMMENDATIONS

These conclusions apply to both canal routes because of similarities in both assessments. However, in a few cases, the discussion pertains to one route only, because of certain unique environmental or human factors involved. These cases are clearly noted.

6.1 Occupational Workers

Primary concern in this study has been devoted to estimating potential doses to native populations that could be affected by the proposed project, but some useful information for protecting the occupational workers has also been developed. Occupational workers are considered here to be any persons engaged in canal construction within the exclusion area, after the time of the first detonation.

Instantaneous dose rates (see Appendix III) are useful for projecting the approximate external radiation hazards at 13 locations along Route 17 for any time up to four years after the initial detonation. Although there are some limitations for the application of these dose rates (discussed in section 4.1.1), they explicitly show that dose rates decrease approximately a factor of 100 during the first month after $H + 24$. Therefore, reentry of occupational workers after individual detonations should be delayed as long as practicable so that maximum protection will result. The significant reductions in potential exposures taking this factor into account would probably justify lengthening the time between detonations in some cases.

After the first detonation, all food and water consumed by occupational workers should be imported from outside the exclusion area. If this precaution is taken, internal exposures from ingestion of radioactive materials will be essentially eliminated. Some internal exposure is possible from dust stirred up by transportation and excavation equipment. During construction, an air monitoring system should be established at each work site, and face masks and respirators should be used if necessary. Revegetation of denuded areas and rainy conditions should decrease the potential inhalation exposures.

All construction-related field work (e.g., road building, clearing forested areas for camp sites, surveys, etc.) that can be completed before the first detonation should be finished by that time in order to keep exposures to the lowest practicable levels.

6.2 Populations Outside the Exclusion Area

In the event that a radioactive "cloud" from a nuclear detonation passes over the exclusion boundary, a significant amount of radioactivity might be deposited on a nearby population center. A potentially hazardous consequence of relocation is that people might be concentrated and living in larger groups (communities, camps, towns, etc.) than formerly, thus making it possible for a large number of people to be exposed simultaneously to a radioactive "cloud" having an unanticipated trajectory.

The following three recommendations are put forth to reduce potential radiological hazards to populations outside the exclusion area from accidental deposition of fallout:

1. Relocate people as far away from the exclusion boundary as practicable, and avoid areas that have more than a remote possibility of receiving fallout (i.e., northwest and southwest boundaries of the exclusion zone in Panama should be avoided).
2. Do not concentrate people so that a large fraction of an ethnic population could be exposed by a single detonation.
3. ~~Emergency~~ planning and indoctrination of all people should be completed before the first detonation.

Locations for temporary residence of evacuated populations should be chosen with care so that the possibility of a stray "cloud" exposing people is minimized. As stated in the first recommendation, these locations for evacuated populations should be as far away from the exclusion boundary as practicable. The second recommendation is intended to reduce the potential genetic dose (assuming that inter-ethnic breeding is negligible) by not permitting a large fraction of an ethnic population to occupy a single area. Even though all precautions might be taken to avoid the possibility of a cloud passing over relocated populations outside the exclusion zone, emergency plans to mitigate the consequences of such an eventuality should be established. This planning should include everyone in each ethnic group and the responsible officials.

The type and extent of emergency action that might be invoked will depend heavily on the effectiveness of a continuing postdetonation monitoring system. Such a monitoring system should be an integration of remote monitors and highly mobile survey teams. Procedures should be worked out beforehand for confiscating or quarantining a food supply,

or for informing everyone to stay under cover while a radioactive "cloud" passes over, if necessary. The principal pathway for the spread of radioactivity from a contaminated watershed to an uncontaminated one is via rivers and streams. Therefore, surface water streams should be monitored in downstream areas where ground contamination may be negligible.

6.3 Reentry of General Population to Exclusion Area

The most effective measure for reducing potential exposures of general populations is to evacuate everyone from areas (exclusion areas shown on Figs. 2.1 and 2.2) expected to receive local fallout. This action is practical because radionuclides contributing most to external dose have short radioactive half-lives (see Appendices II and III for graphs of dose rate as a function of time). For evacuation to be effective, areas to be covered by local fallout must be predicted accurately, and evacuation must be complete.

Assuming fallout predictions are reasonably accurate, evacuation of population groups for 3 years (starting at the time of the first detonation) would eliminate approximately 98 percent of the estimated potential dose from all modes of external exposure (see Table 4.1). The highest potential external dose from the contaminated land surface (considering only the 13 locations studied in this report) could be 3 rems for 67 years of exposure at locations 4 and 5. The actual external dose accrued over this period would probably be much less than 3 rems because environmental factors should reduce considerably the surface dose rate over that period of time, all other factors being equal.

Estimated internal dose resulting from ingestion of contaminated foods and beverages, like the estimated external dose from the contaminated land surface, can be reduced considerably by short delays in reentry during the early post-nuclear-excavation period. Reentry at 5 months, rather than 1 month after the last detonation should reduce estimated maximum annual dose rates to various reference organs due to radionuclide ingestion from watershed 5, Route 17, by factors ranging from 5 to 278, and from watershed 2, Route 25, by factors ranging from 8 to 147. The range in these factors is due primarily to variations in effective half-times of the major dose contributing radionuclides. Similar factors for reentry 30 years, rather than 5 years, after the first detonation range from 1.2 to 7 for both routes. Assuming that the indigenous populations reenter 3 years after the first detonation, the upper estimates of dose commitment due to radionuclide ingestion is 1.6 rems to bone for Route 17; upper estimates of dose commitment for all other reference organs might be lower by a factor of 2.5 or more.

Estimates of maximum somatic dose and genetically significant dose in this report are summations of the dose estimates for only two modes of exposure. It appears, on the basis of these dose estimates (see Figs. 4.2 and 4.3), that delays in reentry extending to 7 or 8 years after the first detonation would result in sizable reductions in doses; beyond that time, further delays of reasonable duration (a few years) would not reduce the estimated doses appreciably.

Although the presence of a sea-level canal would probably produce some changes in basic sustenance for some groups, others, especially the Choco and Cuna Indians, would probably continue their dependence

upon shifting agriculture and fishing for food. Shifting agriculture is utilized because productivity decreases considerably after one or two years of cultivation. When a garden area is cleared, trees and brush are burned in place to release nutrient elements back to the soil. If this technique is continued, any long-lived radionuclides fixed in plant tissues would be released to the soil and thus might become available for uptake by crops. This exposure pathway should be of minor importance, but if the soil is poor nutritionally or lacking in clay minerals, the soil-to-root pathway might be of more than minor importance. Monitoring programs should be designed to detect intakes that might be unique to shifting agriculture techniques.

6.4 Radiological Safety-Feasibility of a Sea-Level Canal Excavated with Nuclear Explosives

Based on the dose estimation studies reported herein, it is our opinion that a definitive assessment of radiological safety is not possible at this time. This opinion is based on recognition of the fact that all potentially hazardous situations have not been evaluated, and for those that have been evaluated, no reliable estimates of accuracy are possible. Although there appears to be a likelihood of wet deposition, resulting in higher potential doses, no input data were provided for rainout conditions.

A realistic assessment of potential radiological hazards cannot be made without more bioenvironmental and radiological information. A larger program of investigation is clearly indicated for a project of this size. The proposed sea-level canal project would involve large land and ocean areas, and affect thousands of people. Any uncertainty about the safety of these people and the possible deleterious

effects on this environment should be reduced to nil before a decision is made to go ahead with the project. For a project of this magnitude and potential impact, educated guesses or unfounded assumptions are not a satisfactory substitute for real data, especially when it is technically and economically feasible to procure the necessary data on which a realistic assessment could be made.

Despite these reservations, we do not appear to have uncovered any radiological problems that could not be managed by adequate planning and reasonable precautions, with but one exception. The nonreleased radioactivity that would remain in the excavation was not considered in our estimates of potential dose. Most of this radioactivity would be trapped far below the bottom of the proposed canal, but the possibility that this radioactivity would be flushed out of the rubble is probably real. There does not appear to be an effective "solution" to this potential problem, nor is it at all certain that the potential exposures resulting therefrom would be significant.

6.5 Further Research to Improve the Estimates of Potential Dose

Since all other subcontractors in the bio-environmental program provided inputs to the dose-estimation study, directly or indirectly, any improvements made in these inputs would improve the estimates. We are not in a position to comment further on the work of others. Therefore, the recommendations which follow are related to improving the input information used directly in the dose estimation study.

Internal dose parameters (biological half-time, fraction assimilated, organ mass, and effective absorbed energy) used in the INREM code are standard-man values or were derived by performing modifications on standard-man data. Further dose estimation studies should include biological parameters specific for the populations involved. Two types of studies are recommended for representative age and ethnic groups: (1) stable element analyses of total diet and total excreta over periods of one month or more, and (2) weight, dimension, and stable element analyses of organs from cadavers.

Also, data should be obtained to evaluate fully the three modes of potential exposure omitted in this study: submersion in air, submersion in water, and inhalation.

Carefully designed radionuclide tracer studies, involving moderately large plots, should be carried out in environments where fallout might be deposited from canal construction. Transfer coefficients or mathematical functions describing intercompartmental transfers of radionuclides are the major data expected from this research. These data could be used (1) to provide better simulations of radionuclide distribution and redistribution in tropical ecosystems, thus resulting in better estimates of potential daily radionuclide intakes, and (2) to estimate the attenuation of the external radiation field above the land surface by processes other than radioactive decay.

APPENDIX I

RADIONUCLIDE IDENTIFICATION.

INDEX	ATOMIC NUMBER	NAME	DECAY CONSTANT (1/HR)	NO. BETA PARTICLES	NO. GAMMA PHOTONS
3	32	GE77	6.13000E-02	7	18
4	33	AS77	1.78000E-02	4	4
5	32	GE78	4.71000E-01	1	2
6	33	AS78	4.57000E-01	7	14
14	35	BR82	1.96000E-02	1	8
16	35	BR83	3.01000E-01	2	4
17	36	KR83M	3.65000E-01	0	2
18	34	SE83	1.66000E 00	3	9
25	36	KR85M	1.58000E-01	1	3
26	36	KR85	7.46000E-06	2	1
31	36	KR87	5.33000E-01	3	4
33	36	KR88	2.48000E-01	3	8
34	37	R888	2.31000E 00	3	10
37	37	R889	2.71000E 00	7	8
38	38	SR89	5.48000E-04	1	0
42	38	SR90	2.83000E-06	1	0
43	39	Y90	1.07600E-02	1	0
46	38	SR91	7.14999E-02	5	5
47	39	Y91M	8.32000E-01	0	2
48	39	Y91	4.90000E-04	2	1
51	38	SR92	2.56000E-01	1	3
52	39	Y92	1.96000E-01	6	10
56	39	Y93	6.93000E-02	5	10
57	40	ZR93	5.27000E-11	1	0
65	40	ZR95	4.44000E-04	4	4
66	41	NB95M	7.70000E-03	0	1
67	41	NB95	8.25000E-04	2	1
69	40	ZR97	4.08000E-02	3	4
70	41	NB97M	4.16000E 01	0	2
71	41	NB97	5.62000E-01	2	2
77	42	MO99	1.03000E-02	3	6
78	43	TC99M	1.14600E-01	0	4
79	43	TC99	3.73000E-10	1	0
84	42	MO102	3.62000E 00	1	0
85	43	TC102M	9.24000E 00	1	1
86	43	TC102	4.99100E 02	1	0
88	44	RU103	7.31000E-04	3	6
89	45	RH103M	7.30000E-01	0	2
94	44	RU105	1.58000E-01	5	11
95	45	RH105M	5.54000E 01	0	2
96	45	RH105	1.93000E-02	2	2
97	44	RU106	7.91000E-05	1	0
98	45	RH106	8.32000E 01	4	5
106	45	RH108	1.49000E 02	4	4
109	67	AG109M	6.40000E 01	0	2
111	46	PO111M	1.26000E-01	0	2

APPENDIX I, Continued

RADIONUCLIDE IDENTIFICATION.

INDEX	ATOMIC NUMBER	NAME	DECAY CONSTANT (1/HRS)	NO. BETA PARTICLES	NO. GAMMA PHOTONS
112	46	PD111	1.89000E 00	0	25
113	47	AG111M	3.33000E 01	0	1
114	47	AG111	3.85000E-03	3	4
115	46	PD112	3.30000E-02	1	2
116	47	AG112	2.17000E-01	4	20
124	47	AG115	2.08000E 00	9	22
125	48	CD115M	6.72000E-04	4	3
126	48	CD115	1.24000E-02	4	6
127	49	IN115M	1.53000E-01	1	2
128	49	IN115	1.32000E-19	1	0
133	48	CD117M	2.04000E-01	0	6
134	48	CD117	2.89000E-01	8	11
135	49	IN117M	3.65000E-01	3	5
136	49	IN117	9.24000E-01	1	3
137	50	SN117M	2.06000E-03	0	3
145	48	CD120	3.47000E 00	1	1
146	49	IN120	5.67000E 01	8	11
154	50	SN123	2.31000E-04	1	2
155	50	SN123M	1.05000E 00	2	1
161	50	SN125	3.07000E-03	5	7
162	51	SB125	2.93000E-05	8	18
163	52	TE125M	4.98000E-04	0	3
167	50	SN127	3.38000E-01	1	1
168	51	SB127	7.45000E-03	4	5
169	52	TE127M	2.65000E-04	0	2
170	52	TE127	7.45000E-02	2	4
171	50	SN128	7.30000E-01	0	5
172	51	SB128M	8.06000E-02	1	3
173	51	SB128	3.85000E 00	1	3
175	51	SB129	1.61000E-01	3	5
176	52	TE129M	8.75000E-04	0	2
177	52	TE129	5.78000E-01	3	4
184	51	SB131	1.81000E 00	1	1
185	52	TE131M	2.41000E-02	4	16
186	52	TE131	1.66000E 00	4	5
187	53	I131	3.57000E-03	4	9
188	54	XE131M	2.45000E-03	0	2
191	52	TE132	8.89000E-03	1	2
192	53	I132	3.01000E-01	6	25
194	52	TE133M	7.85000E-01	2	12
195	52	TE133	3.32700E 00	2	2
196	53	I133	3.41000E-02	2	3
197	54	XE133M	1.26000E-02	0	2
198	54	XE133	5.45000E-03	2	4
202	53	I135	1.03000E-01	3	11
203	54	XE135M	2.60000E 00	0	2

APPENDIX I, Continued

RADIONUCLIDE IDENTIFICATION.

INDEX	ATOMIC NUMBER	NAME	DECAY CONSTANT (1/HRS)	NO. BETA PARTICLES	NO. GAMMA PHOTONS
204	54	XE135	1.61999E-02	2	4
205	55	CS135	2.64000E-11	1	0
207	55	CS136	2.11000E-03	2	8
210	55	CS137	2.64000E-06	2	0
211	56	BA137M	1.60000E 01	0	2
213	54	XE138	2.38000E 00	1	3
214	55	CS138	1.30000E 00	7	12
218	56	BA139	5.02000E-01	3	3
221	56	BA140	2.26000E-03	4	5
222	57	LA140	1.73000E-02	6	12
225	56	BA141	2.31000E 00	1	1
226	57	LA141	1.79000E-01	2	1
227	58	CE141	8.88000E-04	2	2
231	57	LA142	4.50000E-01	9	12
236	58	CE143	2.10000E-02	3	9
237	59	PR143	2.09000E-03	1	0
238	58	CE144	1.02000E-04	3	8
239	59	PR144	2.45000E 00	3	3
241	59	PR145	1.16000E-01	1	0
242	58	CE146	2.97000E 00	3	9
243	59	PR146	1.73000E 00	2	3
245	59	PR147	3.47000E 00	4	8
246	60	ND147	2.60000E-03	3	11
247	61	PM147	3.04000E-05	1	0
250	60	ND149	3.85000E-01	3	10
251	61	PM149	1.31000E-02	5	2
253	60	ND151	3.47000E 00	1	8
254	61	PM151	2.48000E-02	6	25
255	62	SM151	9.09000E-07	2	1
258	62	SM153	1.47000E-02	4	7
261	62	SM155	1.73000E 00	2	4
262	63	EU155	4.37000E-05	4	4
263	62	SM156	7.37000E-02	2	5
264	63	EU156	1.93000E-03	3	21
266	63	EU157	4.59000E-02	2	3
269	63	EU159	2.30000E 00	6	9
270	64	GDI59	3.85000E-02	3	4
272	65	TB160	4.00000E-04	6	19
274	65	TB161	4.19000E-03	3	5
279	79	AU ¹⁹⁵	1.58000E-04	0	2
280	94	PU238	9.15800E-07	0	1
281	94	PU239	3.24400E-09	0	1
282	94	PU240	1.20300E-08	0	1
283	94	PU241	5.99500E-06	1	0
287	79	AU196	4.66000E-03	1	4
288	79	AU198	1.06700E-02	2	4

APPENDIX I, Continued

RADIONUCLIDE IDENTIFICATION.

INDEX	ATOMIC NUMBER	NAME	DECAY CONSTANT (1/HRS)	NO. BETA PARTICLES	NO. GAMMA PHOTONS
289	74	W181	2.06000E-04	0	2
290	74	W185	3.90000E-04	1	0
291	74	W187	2.89000E-02	3	16
292	74	W188	4.19000E-04	3	3
294	82	PB202	2.64000E-10	0	1
295	82	PB203	1.33000E-02	0	4
296	82	PB204M	6.21000E-01	0	4
297	82	PB205	2.64000E-12	0	1
298	82	PB209	2.10000E-01	1	0
299	82	PB210	3.88000E-06	2	1
300	81	TL204	2.08000E-05	1	0
301	80	HG203	6.14000E-04	1	2
302	4	BE7	5.38800E-04	0	1
303	1	H3	6.43300E-06	1	0
304	24	CR51	1.04000E-03	0	3
305	25	MN54	9.53000E-05	0	1
306	25	MN56	2.69000E-01	4	7
307	26	FE55	3.04000E-05	0	1
308	26	FE59	6.33000E-04	4	5
309	11	NA24	4.62000E-02	1	2
310	15	P32	2.02000E-03	1	0
311	20	CA45	1.75000E-04	1	0
312	11	NA22	3.07000E-05	1	1
313	92	U237	4.28000E-03	1	11
314	6	CI4	1.38100E-08	1	0
315	19	K42	5.59000E-02	5	3
316	21	SC46	3.45000E-04	1	2
318	16	S35	3.33000E-04	1	0
319	75	RE188	4.08000E-02	8	6
320	81	TL202	2.41000E-03	0	3
321	83	BI210	5.78000E-03	1	0
334	95	AM241	1.72600E-07	0	10

APPENDIX II

Fig. 1. External Gamma Dose 1 Meter above Landscape
(Location 1, San Miguel, Route 17).

Fig. 2. External Gamma Dose 1 Meter above Landscape
(Location 2, Punta Cocos, Route 17).

APPENDIX II, Continued

Fig. 3. External Gamma Dose 1 Meter above Landscape
(Location 3, Garachine, Route 17).

Fig. 4. External Gamma Dose 1 Meter above Landscape
(Location 4, Rio Congo, Route 17).

APPENDIX II, Continued

Fig. 5. External Gamma Dose 1 Meter above Landscape (Location 5, La Palma, Route 17).

Fig. 6. External Gamma Dose 1 Meter above Landscape (Location 6, Chepigana, Route 17).

APPENDIX II, Continued

Fig. 7. External Gamma Dose 1 Meter above Landscape
(Location 7, Junction Rio Chucunaque & Rio Chiatl,
Route 17).

Fig. 8. External Gamma Dose 1 Meter above Landscape
(Location 8, Uala, Route 17).

APPENDIX II, Continued

Fig. 9. External Gamma Dose 1 Meter above Landscape
(Location 9, Yantupo, Route 17).

Fig. 10. External Gamma Dose 1 Meter above Landscape
(Location 10, Mulstupo, Route 17).

APPENDIX II, Continued

Fig. 11. External Gamma Dose 1 Meter above Landscape
(Location 11, Acla, Route 17).

Fig. 12. External Gamma Dose 1 Meter above Landscape
(Location 12, Sabalo, Route 17).

APPENDIX II, Continued

Fig. 13. External Gamma Dose 1 Meter above Landscape
(Location 13, Ailigandi, Route 17).

APPENDIX III

Fig. 1. External Gamma Dose Rates for Rt. 17, Loc. 1.

Fig. 2. External Gamma Dose Rates for Rt. 17, Loc. 2.

APPENDIX III, Continued

Fig. 3. External Gamma Dose Rates for Rt. 17, Loc. 3.

Fig. 4. External Gamma Dose Rates for Rt. 17, Loc. 4.

APPENDIX III, Continued

Fig. 5. External Gamma Dose Rates for Rt. 17, Loc. 5.

Fig. 6. External Gamma Dose Rates for Rt. 17, Loc. 6.

APPENDIX III, Continued

Fig. 7. External Gamma Dose Rates for Rt. 17, Loc. 7.

Fig. 8. External Gamma Dose Rates for Rt. 17, Loc. 8.

APPENDIX III, Continued

Fig. 9. External Gamma Dose Rates for Rt. 17, Loc. 9.

Fig. 10. External Gamma Dose Rates for Rt. 17, Loc. 10.

APPENDIX III, Continued

Fig. 11. External Gamma Dose Rates for Rt. 17, Loc. 11.

Fig. 12. External Gamma Dose Rates for Rt. 17, Loc. 12.

APPENDIX III, Continued

Fig. 13. External Gamma Dose Rates for Rt. 17, Loc. 13.

APPENDIX IV

Fig. 1. Maximum Internal Dose Resulting from Radionuclide Ingestion (Kidneys, Watershed 5, Route 17).

Fig. 2. Maximum Internal Dose Resulting from Radionuclide Ingestion (Total Body, Watershed 5, Route 17).

APPENDIX IV, Continued

Fig. 3. Maximum Internal Dose Resulting from Radionuclide Ingestion (Bone, Watershed 5, Route 17).

Fig. 4. Maximum Internal Dose Resulting from Radionuclide Ingestion (Liver, Watershed 5, Route 17).

APPENDIX IV, Continued

Fig. 5. Maximum Internal Dose Resulting from Radionuclide Ingestion (Thyroid, Watershed 5, Route 17).

Fig. 6. Maximum Internal Dose Resulting from Radionuclide Ingestion (Testes, Watershed 5, Route 17).

APPENDIX IV, Continued

Fig. 7. Maximum Internal Dose Resulting from Radionuclide Ingestion (Ovaries, Watershed 5, Route 17).

Fig. 8. Maximum Internal Dose Resulting from Radionuclide Ingestion (Lungs, Watershed 5, Route 17).

APPENDIX IV, Continued

Fig. 9. Maximum Internal Dose Resulting from Radionuclide Ingestion (G.I. Tract, Watershed 5, Route 17).

APPENDIX V

Fig. 1. Dose Commitment to Total Body as Result of Radionuclide Ingestion (Cuna Indians, Watershed 5, Route 17).

Fig. 2. Dose Commitment to Total Body as Result of Radionuclide Ingestion (Choco Indians, Watershed 5, Route 17).

APPENDIX V, Continued

Fig. 3. Dose Commitment to Total Body as Result of Radionuclide Ingestion (Negroes, Watershed 5, Route 17).

Fig. 4 Dose Commitment to Total Body as Result of Radionuclide Ingestion (Colonists, Watershed 5, Route 17).

APPENDIX V, Continued

Fig. 5. Dose Commitment to Bone as Result of Radionuclide Ingestion (Cuna Indians, Watershed 5, Route 17).

Fig. 6. Dose Commitment to Bone as Result of Radionuclide Ingestion (Choco Indians, Watershed 5, Route 17).

APPENDIX V, Continued

Fig. 7. Dose Commitment to Bone as Result of Radionuclide Ingestion (Negroes, Watershed 5, Route 17).

Fig. 8. Dose Commitment to Bone as Result of Radionuclide Ingestion (Colonists, Watershed 5, Route 17).

APPENDIX VI

Fig. 1. Maximum Internal Dose Resulting from Radionuclide Ingestion (Kidneys, Watershed 2, Route 25).

Fig. 2. Maximum Internal Dose Resulting from Radionuclide Ingestion (Total Body, Watershed 2, Route 25).

APPENDIX VI, Continued

Fig. 3. Maximum Internal Dose Resulting from Radionuclide Ingestion (Bone, Watershed 2, Route 25).

Fig. 4. Maximum Internal Dose Resulting from Radionuclide Ingestion (Liver, Watershed 2, Route 25).

APPENDIX VI, Continued

Fig. 5. Maximum Internal Dose Resulting from Radionuclide Ingestion (Thyroid, Watershed 2, Route 25).

Fig. 6. Maximum Internal Dose Resulting from Radionuclide Ingestion (Testes, Watershed 2, Route 25).

APPENDIX VI, Continued

Fig. 7. Maximum Internal Dose Resulting from Radionuclide Ingestion (Ovaries, Watershed 2, Route 25).

Fig. 8. Maximum Internal Dose Resulting from Radionuclide Ingestion (Lungs, Watershed 2, Route 25).

APPENDIX VI, Continued

Fig. 9. Maximum Internal Dose Resulting from Radionuclide Ingestion
(G.I. Tract, Watershed 2, Route 25).

APPENDIX VII

Fig. 1. Dose Commitment to Total Body as Result of Radionuclide Ingestion (Cura Indians, Watershed 2, Route 25).

Fig. 2. Dose Commitment to Total Body as Result of Radionuclide Ingestion (Choco Indians, Watershed 2, Route 25).

APPENDIX VII, Continued

Fig. 3. Dose Commitment to Total Body as Result of Radionuclide Ingestion (Negrees, Watershed 2, Route 25).

Fig. 4. Dose Commitment to Total Body as Result of Radionuclide Ingestion (Colonists, Watershed 2, Route 25).

APPENDIX VII, Continued

Fig. 5. Dose Commitment to Bone as Result of Radionuclide Ingestion (Cuna Indians, Watershed 2, Route 25).

Fig. 6. Dose Commitment to Bone as Result of Radionuclide Ingestion (Choco Indians, Watershed 2, Route 25).

APPENDIX VII, Continued

Fig. 7. Dose Commitment to Bone as Result of Radionuclide Ingestion (Negroes, Watershed 2, Route 25).

Fig. 8. Dose Commitment to Bone as Result of Radionuclide Ingestion (Colonists, Watershed 2, Route 25).