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J. P. Corley
T. H. Essig

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COMPOSITE ENVIRONMENTAL DOSE ESTIMATES[a]

J. P. CORLEY and T. H. ESSIG[b]

PACIFIC NORTHWEST LABORATORY
BATTELLE MEMORIAL INSTITUTE
RICHLAND, WASHINGTON

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(b) Environmental Evaluations, Radiation Protection, Technical Services Division, Pacific Northwest Laboratory, operated by Battelle Memorial Institute for the United States Atomic Energy Commission, Richland, Washington.

COMPOSITE ENVIRONMENTAL DOSE ESTIMATES

ABSTRACT

The occupational hygienist is not unfamiliar with the integrated exposure assessment concept. Many examples of accumulative poisons, carcinogens, and other degenerative disease producing agents are known. In these cases, we have analogous situations to radiation exposures from mixed sources. Discussion of a health physics approach to a specific radiation situation may be of value in illustrating certain concepts that may be more widely applied to a non-radioactive pollution situation.

The population doses received from radionuclides released to the environs are superimposed on those from natural radiation sources plus a minor contribution from weapons testing fallout. Valid estimates of these doses require a knowledge not only of external radiation levels, but also of the kinds and quantities of radionuclides present in the atmosphere and in foods and beverages, and to what extent these radionuclides are transmitted to man through the food chains.

Both the control of plant effluents and the evaluation of an environmental situation arising from the releases of such effluents require comparison of measured or calculated values against appropriate standards. Water and air quality standards for non-radioactive contaminants are generally in terms of concentration limits. Standards for radiation protection, however, are based on accumulated radiation doses over an extended period of time.

In order to quantify the effects of various radionuclides on the different organs of the human body, the International Commission on Radiological Protection has adopted the concept of a "standard man", with assigned biological and physical parameters. The primary radiation dose standards have been translated into secondary standards (Maximum Permissible Body Burdens) and tertiary standards (Maximum Permissible Concentrations in air and water) as additional tools for evaluation. Using the same parameters, one can convert the intake of any one radionuclide into radiation dose. The ingested amount of a radionuclide can be estimated by multiplying the concentrations of the radionuclide in beverages and foods by the consumption rates. The intakes of several radionuclides cannot be combined directly, since each radionuclide results in a numerically different dose per unit intake for each body organ. The total dose received by a body organ of interest is obtained by adding the doses resulting from each radionuclide ingested to the dose resulting from sources external to the body. This total dose can then be compared with appropriate dose standards.

The application of these principles at the Hanford complex has required a major effort in the determination of the critical pathways and the significant dietary intakes. We believe that the future will see more wide-spread use of integrated exposure assessment, particularly in environmental situations. Such use should incorporate these key steps:

1) The investigation of all potential exposure pathways
2) The determination of appropriate air, water, and food intake and contaminant concentrations
3) The appropriate weighting and summation of each source contributing to a common physiological effect.

COMPOSITE ENVIRONMENTAL DOSE ESTIMATES

The health physicist is accustomed to considering the total radiation dose* received by an individual, regardless of source. This approach is perhaps natural in that the physiological insult with which the health physicist is concerned is due to a common physical phenomenon, the absorption of ionizing radiation, regardless of location or chemical form of the radioactive material. In many radiation exposure situations, of course, there may be a single source. The dose evaluation problem in this case is relatively simple. Similarly, an integrated assessment of biological risk is not generally required of occupational hygienists for non-radioactive contaminants. The reasons for the non-integrated approach include:

1) For many contaminants, especially for industrial exposures, only one source may be significant,

2) Exposure limits for non-radioactive toxic materials have generally been established in terms of concentrations in specific media,

3) Many non-radioactive contaminants have only a temporary effect and an integrated long-term exposure consideration may not be meaningful,

4) The physiological effect may vary widely with the source and chemical nature of the contaminant,

5) For environmental exposures, different agencies monitor the levels in the potential sources of air, water, and foodstuffs.

On the other hand, the occupational hygienist today is certainly not unacquainted with the integrated exposure concept. Many examples of accumulative poisons, carcinogens, and other degenerative disease-producing agents are known. There has been much discussion of the potential hazard of lead accumulation in our environment. The more recent "Threshold Limit Values" publications of the American Conference of Governmental Industrial Hygienists[4] point out the need for adding the effect of components of a mixed exposure, where the several components have a common physiological effect. In the future, we would expect even greater attention to long-term latent effects from chronic low-level exposures.

In these cases, we have analogous situations to radiation exposures from mixed sources. Discussion of a health physics approach to a specific situation

* Throughout this paper, the authors will use the shorter term "dose", even though the meaning may more strictly be "dose-equivalent", the appropriate measure of risk of biological effect. References (2) and (3) give explanations of the relationship between the terms.

may then be of value in illustrating certain concepts and principles that may be more widely applied to a non-radioactive pollution situation. We have chosen to discuss environmental radiation exposure because such situations are generally more difficult to monitor and evaluate than occupational exposures, especially for ingestion and inhalation. However, the same principles and concepts apply to either the occupational or the environmental case.

The determination of radiation doses to the population in the vicinity of a nuclear facility from radioactive waste discharges can indeed be most complex. In part, this is due to the superimposition of any such doses on a much larger and varying mixture of radiations from both natural sources and occasionally weapons test fallout. For a typical Richland resident, for example, the whole body dose from Hanford plant releases (mostly from reactor cooling water discharged to the Columbia River, the source of Richland drinking water) is only about 4% of that from natural radiation sources and about the same as the dose due to fallout. Near commerical power reactors, on the other hand, radiation doses to the environmental population from the plant may be smaller than the contribution from fallout and negligible by comparison with natural sources.

Where measureable increases in local radiation levels do occur, valid estimates of the resulting doses to the population may well require a knowledge not only of external radiation levels but also of the specific nuclides present in various environment media, as well as the extent to which these are transmitted to humans through the various food chains. The need for such knowledge arises because of the potential for re-concentration of specific radionuclides at various steps in the food chain, factors for which may exceed 10^5. Our first 3 figures (originally prepared for testimony by H. M. Parker at a Congressional hearing in 1959) illustrate the potential complexity of the fate of some radionuclides and their passage through food chains leading to human consumption. (Figures 1-3)

The pathways of human exposure are fortunately limited, since the local resident will not be eating river algae or alfalfa. None-the-less, a major screening program may be necessary to insure that none of the many types of human foods or recreational habits result in an unsuspected pathway of radiation exposure. If the potential contributions of all potential pathways of exposure are known and release rates are sufficiently low, the monitoring and dose evaluation tasks will, of course, be greatly simplified.

Standards for Radiation Exposures

Both the control of plant effluents and the evaluation of an environmental situation arising from the release of such effluents require comparison of measured or calculated values against appropriate standards. Water and air quality standards for non-radioactive contaminants are generally in terms of concentration limits. For industrial exposures to toxic materials, we have threshold limit values which are, in most cases, time-integrated concentration limits. Standards for radiation protection, however, are based on accumulated radiation doses over an extended period of time to the whole body and specific organs of the body. This basis is not always clear, since regulatory statements may be in the form of secondary and tertiary standards. The relationship between the various types of standards may be made clearer by reference to this chart, originally prepared by J. K. Soldat of Battelle-Northwest. (Figure 4)

> Note that as monitoring is shifted from the source (the plant effluent) toward the person exposed, one needs to make fewer and fewer assumptions but is faced with an increasingly difficult monitoring task. Standards based on permissible doses are found, for example, in the recommendations of the International Commission on Radiological Protection[1,2,3], an international body established for the purpose of formulating authoritative standards for radiation protection. With the use of appropriate physical and physiological parameters, maximum permissible doses to various organs of the body may be translated into maximum permissible dose rates from external sources or maximum permissible body burdens for radionuclides deposited in the body. Assumptions of liquid and air consumption permit calculations of maximum permissible concentrations in these media, and still further assumptions and mathematical treatment permit calculation of maximum permissible release limits. Of course, some monitoring at the source will generally be required in any case for operational control.

It may be appropriate to point out here that for the chronic low-level radiation doses being considered, a direct cause-effect relationship of radiation injury to a specific individual cannot be demonstrated. Conservatively, we may proceed on the assumption that any radiation dose, however small, involves some degree of risk. The standards than are an attempt to select permissible dose levels at a point where the degree of risk of any biological effect is still acceptably low. The term "maximum" should therefore be interpreted in the sense that a small excess of accumulated dose does not represent a significantly increased risk, while the term "permissilbe" does not imply that no risk exists at the level given. Difficulty with such semantics has led the Federal Radiation Council, among others, to avoid the term "maximum permissible" in favor of the term "Radiation Protection Guides". Parenthetically, it should be said that a similar interpretation should be applied to Maximum Allowable Concentrations for non-radioactive toxicants[4].

The basic dose standards recommended by the ICRP are generally used directly for workers occupationally exposed to radiation, when the dose received is largely due to external sources. The ICRP itself, however, has provided both secondary (Maximum Permissible Body Burdens of internally-deposited radionuclides) and teritary standards (Maximum Permissible Concentrations in air and water). In contrast, the most authoritative body in the country, the Federal Radiation Council, has promulgated intermediate standards[5] for non-occupational doses in terms of total intake of several nuclides. The Atomic Energy Commission in its regulations for its contractors[6] and for federal licensees[7] provides alternative standards, either integrated radiation dose or maximum permissible concentrations in air and water. Some states, Washington for example[8], have adopted only the maximum permissible concentration values in their regulations for state licensees for doses from inhalation or ingestion.

It is important to remember where dealing with such standards that the basis remains an integrated dose from all sources to specific body organs.

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The applicable quote from the ICRP recommendations[3] is:

> "In any organ or tissue, the Dose Equivalent is the sum of the Dose Equivalents contributed by both external and internal sources." (para. 71)

Similarly, the Federal Radiation Council recommendations are based on total intake from all sources. The weakness of any standards expressed only as concentrations, without regard to potential re-concentration in the environment, multiple sources of intake, or potential contributions from external sources, should be recognized.

Methods of Calculation

In order to quantify the effects of various radionuclides on the different organs of the human body, the International Commission on Radiological Protection (ICRP) has adopted the concept of a "standard man"[1], with assigned biological and physical parameters. These parameters include: mass of the total body (70 kg), mass of individual organs, effective dimensions and biological elimation constants for each organ, water intake rate (2.2 ℓ/day), and air inhalation rate (20 m^3/day). The parameters for water and air balance are expressed in terms of both the 8-hour work day and the 16 hours not at work. This time separation is made to distinguish occupational from non-occupational exposure to radionuclides, and is necessary because different limits may apply to each type of exposure, and because intake rates of water and air are different during the two time periods.

Radiation dose standards are then assigned to the "standard man", who is deemed to represent all adult individuals or groups of individuals exposed to radiation. The actual standards for annual dose are about an order of magnitude below those showing detectable effects for most acute exposures, and about two orders of magnitude below those radiation doses considered lethal to humans.

Relationships between the primary dose standards, secondary standards (Maximum Permissible Body Burdens), and tertiary standards (Maximum Permissible Concentrations) are shown in Figure 5. (Figure 5)

The first equation relates the Maximum Permissible Body Burden (q) to a permissible dose rate (R). The second and third equations relate the Maximum Permissible Concentrations in air and water (MPC_a and MPC_w) to the Maximum Permissible Body Burden. The two latter equations have an exponential term which represents a combination of biological removal and radioactive decay. These equations do not apply to the GI tract because the passage of food through the tract is assumed to behave as a step function rather than as an exponential function.

These equations provide a basis for dose conversion factors which relate the dose received by an organ to the intake of any radionuclide. Any synergistic effects or variation in physiological behavior with chemical form are usually ignored at the low levels to which environmental populations are normally exposed. (Figure 6)

Figure 6 shows the methods used to calculate such factors for several organs of the body.

The dose increments received by an organ from each deposited radionuclide are simply added to determine the total dose.

An additional radiation dose that must be considered is that received from sources external to the body. The dose contribution from these sources is obtained from measurements of ambient radiation levels and estimates of exposure times. The total dose to a specific organ of the body is then determined by adding the dose contribution from internally deposited radionuclides to the dose resulting from external sources. This total dose can then be compared with the maximum permissible dose for the particular organ.

It is not feasible to determine actual radiation doses received by people in the environs of a nuclear facility by sufficiently large-scale routine personal dosimeter, bioassay, or whole body counting programs. These doses must therefore be calculated. An integral part of the dose calculation scheme therefore is the determination of appropriate radionuclide intakes. The data for this determination can be obtained from a comprehensive environmental surveillance program in conjunction with estimates of dietary and living habits of the environmental population. A comprehensive environmental surveillance program should provide data on radionuclide concentrations in foods and beverages (in the diets of the population groups of interest), on ambient radiation levels, and on radionuclide concentrations in the atmosphere. Knowledge of local food and beverage per capita consumption rates may be obtained from routine dietary studies conducted by various governmental agencies and from local estimates. Ideally, all dietary data should be of local origin. However, a complete collection of local data is difficult to obtain, and one must rely on published dietary data which are often only applicable in a general sense to one's own local situation.

After the radionuclide concentrations in beverages and foods and the appropriate dietary habits are determined, radionuclide intakes can be computed by multiplying the concentration by the consumption rate of the particular beverage or food. The intake of each radionuclide cannot be combined directly, since each radionuclide results in a numerically different dose per unit intake for each body organ. As mentioned earlier, the intake of each radionuclide must be converted to units of dose in order to form a combination which represents the total organ dose.

Hanford Environmental Program

The application of these principles at the Hanford complex has required a major effort in the determination of critical exposure pathways and significant dietary intakes. To repeat, the five steps in the dose calculation process are: 1) obtaining dietary data, 2) determining radionuclide concentrations, 3) determining radionuclide intakes, 4) calculating radiation dose and 5) comparing with dose standards.

The acquisition of dietary data required a major initial effort and a smaller continuing effort to optimize the data. The dietary intakes currently used for the population in the Hanford environs are shown in Figure 7. (Figure 7)

These data were obtained from a number of sources, including published dietary surveys conducted by various government agencies, a large body of data from local diet questionnaires obtained in conjunction with whole-body counting programs, and special mail and personal interview surveys of consumers of local fish and game. Diets are listed for both a "maximum individual" and a "typical Richland resident". These hypothetical population segments were selected as control groups for comparison with the appropriate AEC standards. Attempts have been continued to identify the types of individuals living in the Hanford environs that receive the greatest radiation dose. Experience accumulated from the environmental surveillance program indicates such individuals are undoubtedly persons that frequently eat both fish caught locally in the Columbia River and foodstuffs grown on farms irrigated with Columbia River water. The vast majority of people who live in Richland obtain their food from local commercial stores (rather than directly from farms) and consume little or no fish caught from the Columbia River. The principal sources of radionuclides ingested by these people are drinking water obtained from the Columbia River and worldwide fallout.

The second step of the dose calculation process, determining radionuclide concentrations, requires a major, continuing effort. In a recent year, for example, the environmental dose evaluation program at Hanford included some 700 water samples, 300 air samples, 500 milk samples, 100 samples of garden produce, and 1500 samples of fish, game birds, and sea food. Approximately 500 external radiation measurements were also used in this program. These statistics do not include many other measurements made solely for trend evaluation or detection of unusual releases. A summary of radionuclide concentrations in foods and beverages during 1966 for the two population groups of interest is shown in Figure 8. (Figure 8)

When data obtained from these two steps are combined, radionuclide intakes and the resulting doses can be calculated. After the external dose contribution is added a dose composition such as shown in Figure 9 can be determined. (Figure 9)

The doses calculated for the four organs shown ranged between 1 and 10% of the appropriate limit. The relative contribution of the various sources to the total for each organ are apparent.

The situation presented here is of course unique to the Hanford site, as are most exposure situations, whether to radioactive or non-radioactive materials. Only Hanford, among U. S. nuclear facilities, routinely conducts such a broad radiation dose estimation program, although similar efforts have been made intermittently elsewhere[9]. For most installations, the impact on environmental radiation levels is so slight that such a comprehensive program is not warranted for routine operations. We believe, however that these mehtods can be applied to any exposure situation involving more than one mode of exposure.

We further believe that the future will see more wide-spread use of integrated exposure assessment, particularly in environmental situations.

To be successful, such use must incorporate these key steps:

1) The investigation of all potential exposure pathways
2) The determination of appropriate air, water, and food intakes and contaminant concentrations
3) The appropriate weighting and summation of each source contributing to a common physiological effect

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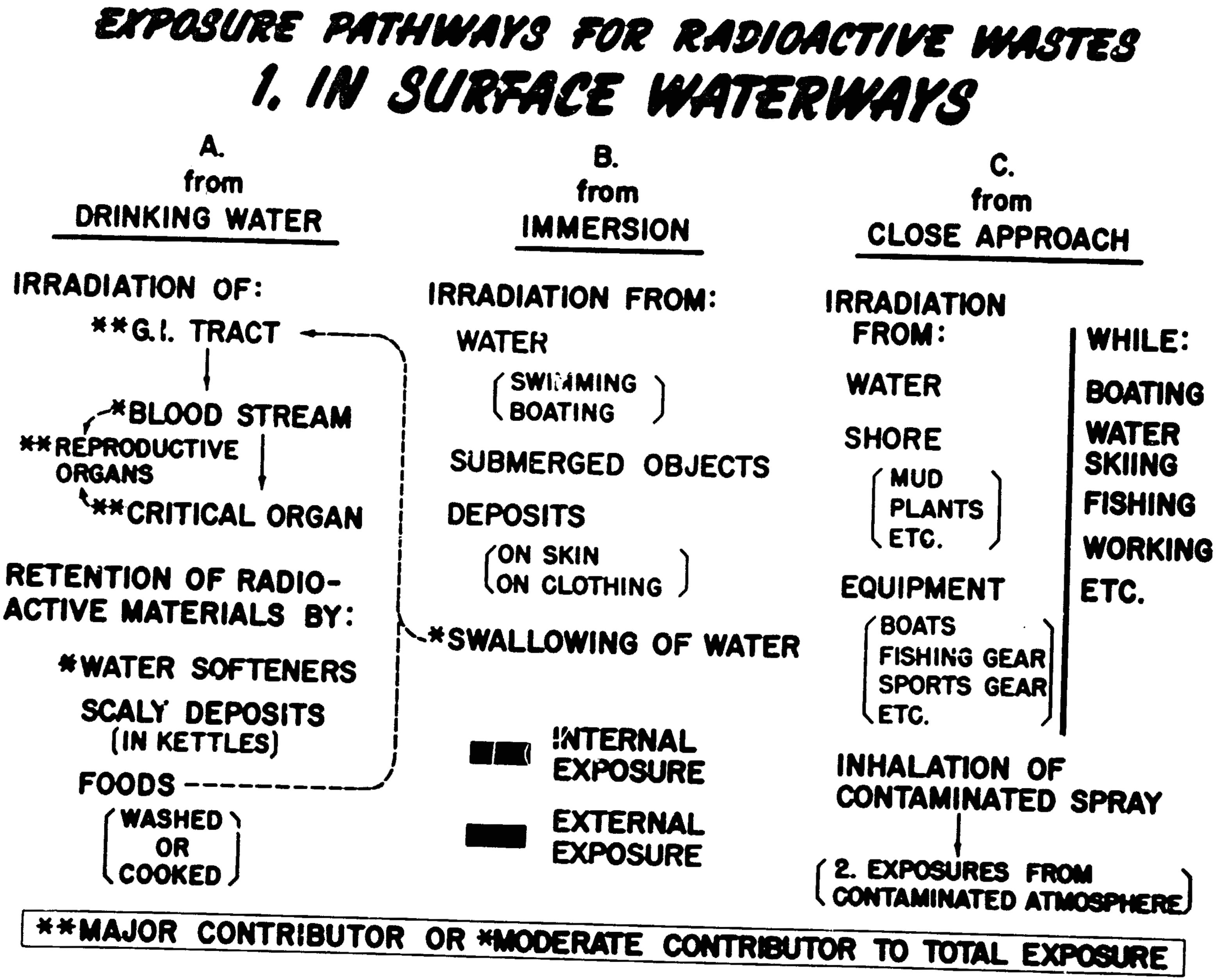

FIGURE 1

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EXPOSURE PATHWAYS FOR RADIOACTIVE WASTES
1. IN SURFACE WATERWAYS

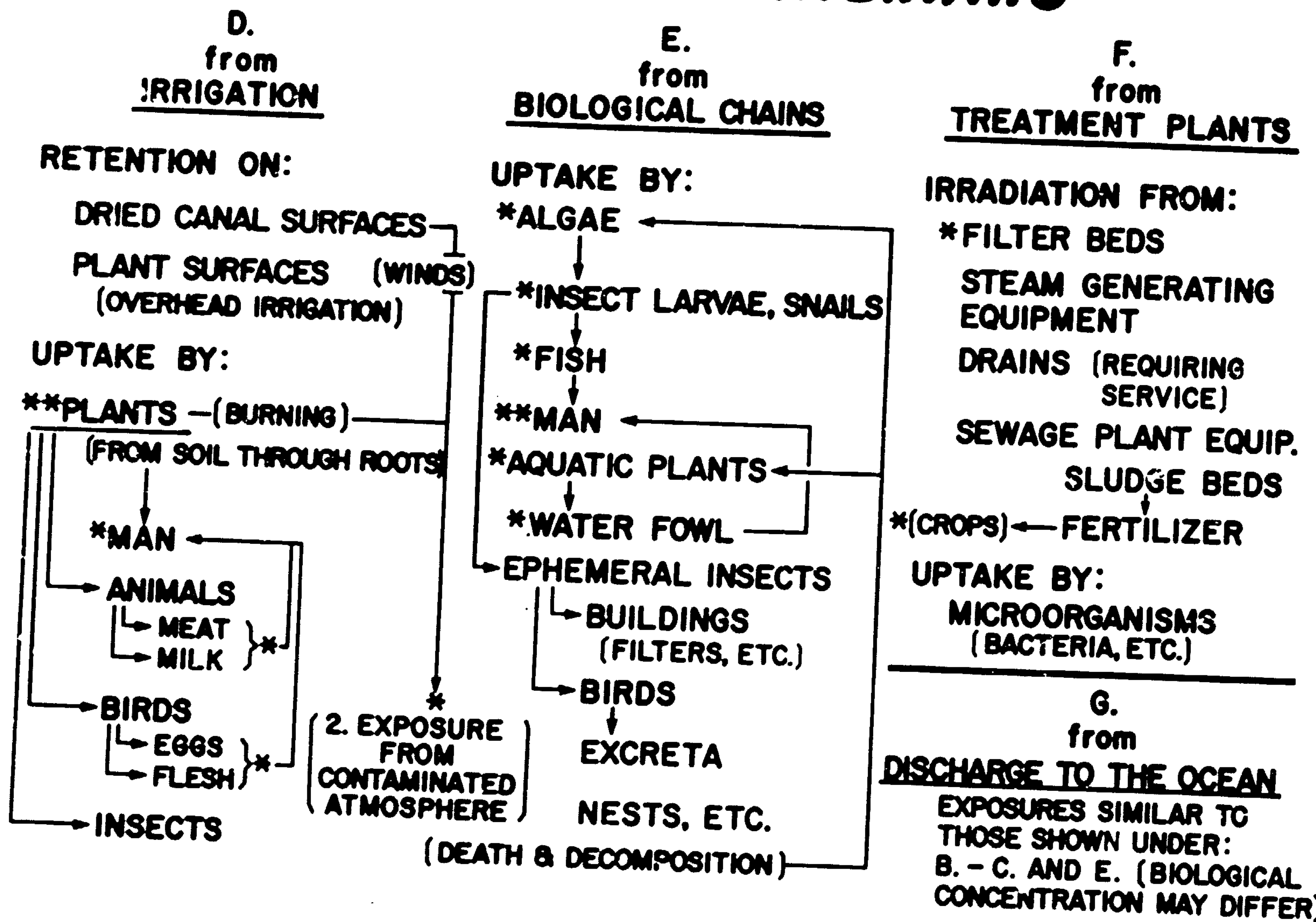

FIGURE 2

EXPOSURE PATHWAYS FOR RADIOACTIVE WASTES
2. IN THE ATMOSPHERE

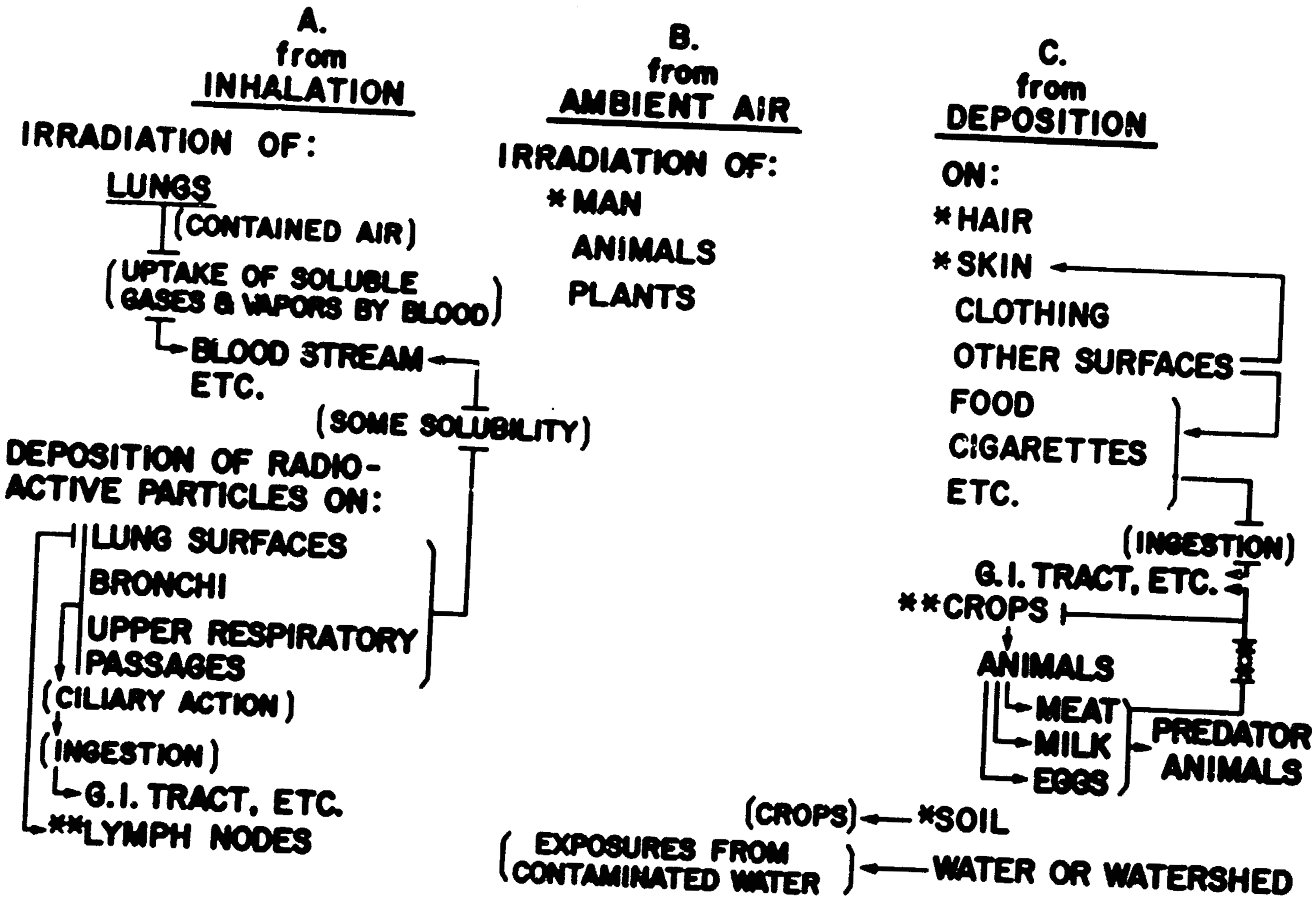

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FIGURE 3

	STEP	FACTORS	EVALUATION	STANDARDS
A.	Release	Concentration, Rate of Release	Measure Effluent	Release Guides
B.	Dispersion, Reconcentration	Meteorology, Hydrology, Physical and Chemical Forms	Measure Environmental Media - Air, Water, Foods	Fraction of MPC_w or MPC_a (Concentration Factors)
C.	Intake	Air, Water, Food } { Concentration, Consumption, Rate	Diet Surveys, Uses of Environs Studies	FRC Ranges, ICRP - μCi/day
D.	Retention	Percent Uptake, Biological Half-Life, Distribution in Body	Bioassay, Whole-Body Counting	M. P. B. B.'S
E.	Dose	Body Dimensions, QF, DF, Rads/μCi	Calculate Doses to - Maximum Individual, Population Average, Adult, Child	AEC Manual, FRC Reports, NCRP H.B.'S, ICRP H.B.'S

FIGURE 4
Evaluation Chart - Environmental Population Dose

PERMISSIBLE DOSE RATE, BODY BURDEN, AND MPC'S

$$q = \frac{0.0028 \text{ mR}}{f_2 \epsilon}$$

$$MPC_a = \frac{10^{-7} \, q f_2}{T f_a \left[1 - \exp(-0.693 \, t/T)\right]}$$

$$MPC_w = \frac{9.2 \times 10^{-4} \, q f_2}{T f_w \left[1 - \exp(-0.693 \, t/T)\right]}$$

REFERENCE: ICRP PUBLICATION 2
SEC. IV, 1959

FIGURE 5

DOSE FACTOR (GI TRACT AND WHOLE BODY) $= \frac{MPD}{(MPC_w)(FI)} = \frac{mrem/yr}{(\mu Ci/ml)(ml/day \times 365\ days/yr)}$

DOSE FACTOR (THYROID) $= \frac{MPD}{IG} = \frac{mrem/yr}{pCi/day \times 10^{-6}\ \mu Ci/pCi \times 365\ days/yr}$

DOSE FACTOR (BONE) $= \frac{100\%}{(MPC_w)(FI)} = \frac{100\%}{(\mu Ci/ml)(ml/day \times 365\ days/yr)}$

WHERE FI = FLUID INTAKE RATE FOR ICRP STANDARD MAN = 2200 ml/day

AND IG = FRC INTAKE GUIDE FOR ^{131}I

FIGURE 6
Radiation Dose Factors Cont'd.

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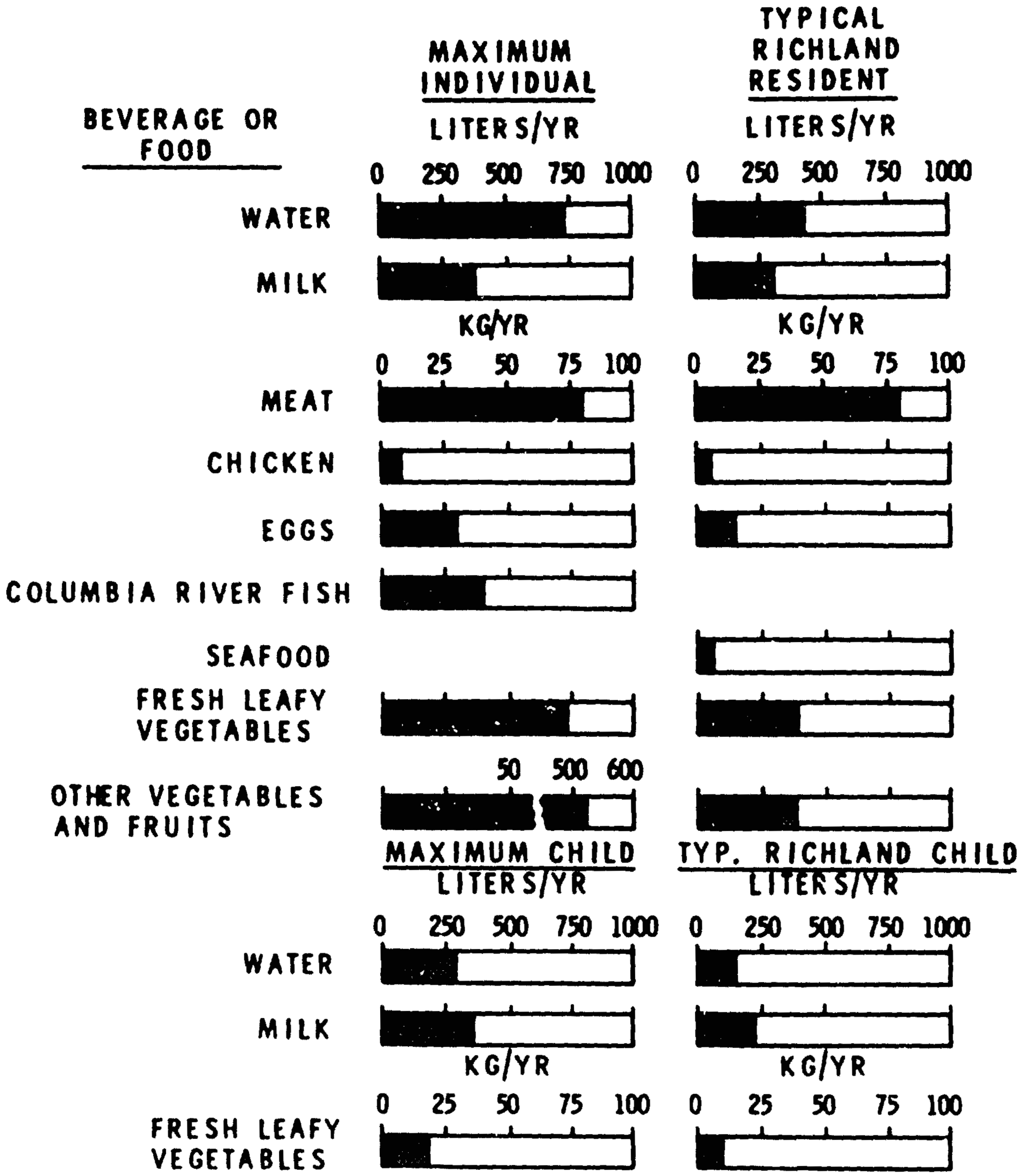

FIGURE 7
Dietary Assumptions for the Adult and Child

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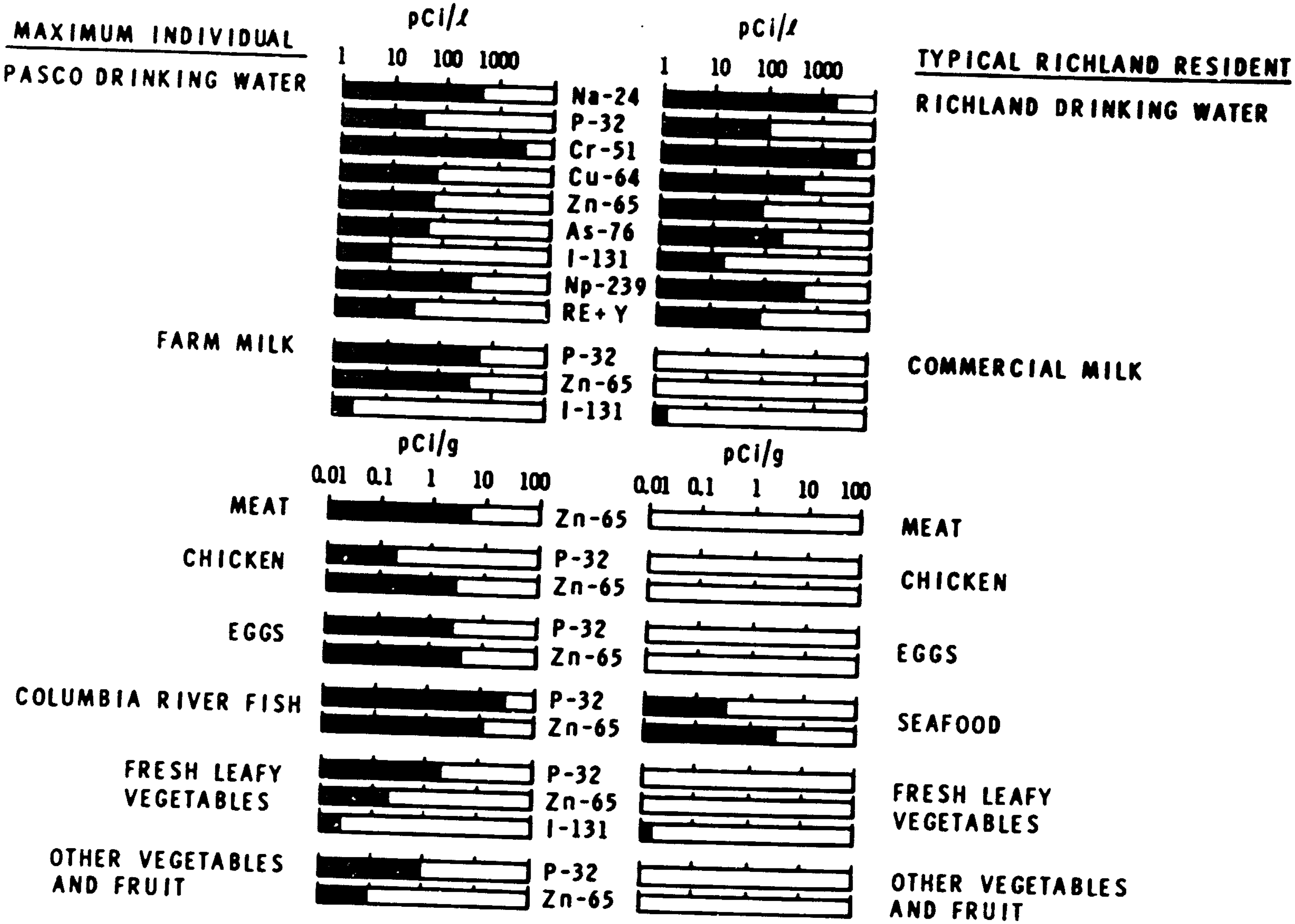

FIGURE 8

Radionuclide Concentrations in Beverages and Foods - 1966

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RELATIVE SOURCE CONTRIBUTION (HANFORD ENVIRONS) - 1966

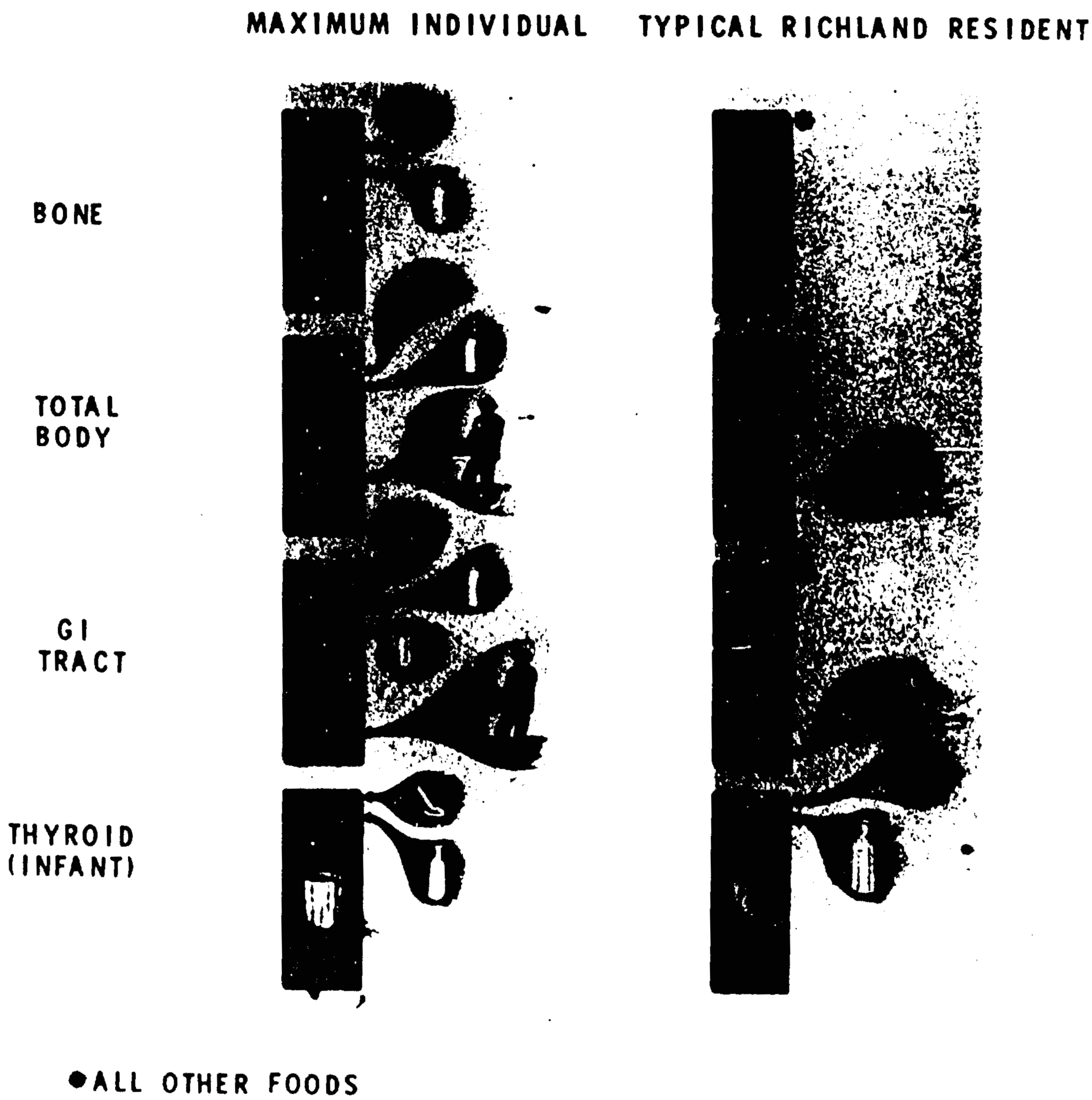

FIGURE 9

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