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CRITERIA FOR ESTABLISHING SHORT TERM PERMISSIBLE INGESTION OF FALLOUT MATERIAL

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The criteria for establishing permissible ingestion of radioactive fallout material under emergency conditions for times immediately following a nuclear detonation are dependent primarily on exposures to the,

a. gastrointestinal tract from the gross fission product activity,

b. thyroid from the isotopes of iodine and,

c. bone, principally from Sr^{90}- Y^{90}, Sr^{89}, Ba^{140}-La^{140}

I. Doses to the Gastrointestinal Tract

The following principal assumptions are used in calculating the doses to the gastrointestinal tract of adults:

a. The calculations are based on the methods contained in reference one.

b. The fallout material is insoluble. (See V. Discussion below)

c. The activity decays according to the principle of $(\text{time})^{-1.2}$.

d. The energy delivered is all derived from the beta emissions, having a mean energy of 0.5 Mev when in the lower large intestine. (See Graph One[2])

Range in $H_2O \cong .7$ mm

e. The total daily consumption of food and water is 2200 grams or milliliters.

The method of calculation is according to the following equation:

$$\frac{(\text{Total number of disintegrations occurring in organ})(\text{Energy of emissions})(8.0\text{x}10^{-9})}{(\text{Mass of Organ})} = \text{Dose (rads)} \quad (1)\ *$$

The number of disintegrations taking place in the organ may be calculated according to equation two:

$$\text{Total number of disintegrations} = 5A_a\, t_a^{1.2} [t_a^{-0.2} - t_b^{-0.2}] \quad (2)$$

Where: A_a = number of disintegrations per unit time at time "a" after detonation

t_a = time "a" after detonation

t_b = time "b" later than "a"

Range to come in 4 hr
in [illegible] in 18 hrs

One of the more useful forms for the criteria would be in units of permissible concentrations at time of intake. This will somewhat complicate the calculations since there will be a decrease in activity as the material passes along the gastrointestinal tract. When such calculations are made according to the above assumptions and equations, it may be seen that the critical organ is the lower large intestine except for the first hours immediately following the detonation. (Table One shows the relative doses to parts of the gastrointestinal tract as a function of time.) Therefore, Graph Two is based on the activity at time of ingestion to produce one rad of dose to the lower intestine.

For example, Graph Two shows that if about 34 microcuries are ingested on the 24th hour after detonation, the lower large intestine

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*The rad is the unit of absorbed dose and is 100 ergs per gram.

may receive one rad of radiation dose. This was calculated in the following manner.

Step 1. Determine the total number of disintegrations in the lower large intestine necessary to produce 1.0 rad.

From equation (1)

$$\frac{(\text{Number of disintegrations})\ (0.5)\ (8.0 \times 10^{-9})}{150} = 1$$

$$\text{Number of disintegrations} = 3.8 \times 10^{10}$$

Step 2. Determine the activity at time of intake to produce 3.8×10^{10} disintegrations within the large intestine.

From equation (2)

$$3.8 \times 10^{10} = (5)\ (A_{37})\ (37^{1.2})\ [37^{0.2} - 55^{-0.2}]^{*}$$

$$A_{37} \cong 2.7 \times 10^{9}\ \text{d/hr.}$$

$$A_{24} \cong 4.5 \times 10^{9}\ \text{d/hr.}$$

$$A_{24} \cong 34\ \mu c$$

* If the time of intake is the 24th hour, then the start of irradiation of the lower large intestine is $24 + 13 = 37^{th}$ hour.

Graph Two has been used in estimating radiation doses to the lower large intestine for prolonged periods of ingestion (Table Two). The following calculations are illustrative for the period of 24th to the 120th hour (start of intake at the beginning of the 2nd day after detonation for a duration of four days).

Step 1. Determine the number of microcuries at time of ingestion to produce 1.0 rad to the lower large intestine.

From Graph Two take the mid point of intake period (74th hour) → 22μc (This is obviously an approximation since the exact times of intake during the four-day period will be unknown).

Step 2. Determine the activity at time of intake.

From equation (2)

$$22 = 5 A_{24}\, 24^{1.2} \left[24^{-0.2} - 120^{-0.2} \right]$$

$$A_{24} \cong 0.67 \ \mu c/hr$$

Since there is assumed a 2200 ml/day intake

$$0.67 \times \frac{24}{2200} \cong 0.0073 \ \mu c/ml \text{ or gm}$$

II. Doses to the Thyroid

The following principal assumptions are used in calculation the doses to the adult thyroid from oral intake of activity from fallout material:

a. The percentages of the isotopes of iodine in mixed fission products are according to Hunter and Ballau.[3]

b. Twenty percent of the ingested I^{131} reaches the thyroid.

c. The mean energy is 0.22 Mev.

d. The thyroid weight is 20 grams. (See V. Discussion below)

e. The percentages of shorter-lived isotopes of iodine that reach the thyroid and their doses are according to reference four.

The method of calculation of doses to the thyroid is illustrated by computing that amount of intake of fission products at the 48th hour to produce 1.0 rad.

Step 1. Determine the dose rate on the day of intake of I^{131} to produce 1.0 rad to the thyroid.

$D = \frac{R}{\lambda_e}$ Where: D = dose (1.0 rad)
R = dose rate on initial day
λ_e = effective decay constant (Radiological and biological)

$$1.0 = \frac{R}{0.09}$$

$R = 0.09$ rads/day

Step 2. Determine the number of microcuries of I^{131} to produce 0.09 rad/day

$$\frac{X(\mu c)\ (2.2 \times 10^{6})\ (60 \times 24)\ (1.6 \times 10^{-6})\ (0.22)}{(100)\ (20)} = 0.09$$

$X = 0.16\ \mu c$ to thyroid
or
$(0.16)\ (5) = 0.80\ \mu c$ I^{131} ingested

Step 3. Determine relative doses from I^{131} and I^{short} according to Graph Three.[4]

At 48th hour, the relative contribution to total dose from I^{131} and I^{short} is about $\frac{1}{1}$.

Therefore, ingestion of 0.4 μc I^{131}(equivalent) at 48th hour will produce 1.0 rads to thyroid.

Step 4. Determine the number of microcuries of fission products required to yield the required I^{131} activity. At 48th hour, I^{131} constitutes about 2.35% of total activity. Therefore,

$$\frac{0.4}{0.023} \cong 17\ \mu c \text{ of fission products.}$$

Graph Four shows the number of microcuries of fission products ingested at times after detonation to produce 1.0 rad to the thyroid.

III. Doses to the Bones

The three principal bone-seeking isotopes of concern are Sr^{90}-Y^{90}, Sr^{89}, and Ba^{140}-La^{140}. Evaluation of these may be made in terms of amount deposited in the bones versus maximum permissible body burdens, or in rads of dose that they deliver after deposition. Since values for maximum permissible body burdens are based on the concept that these will be maintained indefinitely in the body, they are not so valid for Sr^{89} and Ba^{140}- La^{140} when considering short periods of emergency intake.

The following principal assumptions are used in calculating the doses to the bones of adults:

a. The percentages of the isotopes of Sr^{90}-Y^{90}, Sr^{89}, and Ba^{140} - La^{140} in mixed fission products are according to Hunter and Ballau.[3]

b. The percentages of intake of these isotopes that are deposited in the bones, the energies of emissions, and their effective half lives are according to reference five - except for Sr^{90} where a 27.7 year radiological half life is used here.

c. The mass of the bones is 7,000 grams.

The method of calculation of doses to the bones is illustrated by computing the dose from Sr^{89} from the intake of 11 microcuries (See V. Discussion below) of mixed fission products on the 20th day.

Step 1. Determine the Sr^{89} to reach the bone.

According to reference four:

The Sr^{89} content in mixed fission products on the 20th day is 5%.

According to reference five:

The intake of Sr^{89} to reach to the bones is 25%.

Therefore:

$$(11)\ (0.05)\ (0.25) \cong 0.14\ \mu c, \text{ to the bones.}$$

Step 2. Determine the dose rate to the bones.

With an assumed effective energy of 0.55 Mev (reference 5)

$$\frac{(0.14)\ (2.2 \times 10^{6})\ (60 \times 24)\ (1.6 \times 10^{6})(0.55)}{(100)\ (7{,}000)} = 5.6 \times 10^{-4} \text{ rads/day}$$

or 0.56 millirads/day

Step 3. Determine total dose

$D \text{ total} = \frac{R}{\lambda e}$ where: R = initial dose rate

λe = effective decay constant

$$D \text{ total} = \frac{0.56}{0.0133} \cong 42 \text{ millirads}$$

IV. Methods For Estimating Doses For Prolonged Periods Of Intake

As suggested above, the thyroid receives greater doses than do the gastrointestinal tract or bones for periods of intake out to about 20 days after a detonation (except for the first day). If permissible intakes were based on the thyroid dose only, then Graph Four indicates that there could be an increasing intake of fission product activity after about the 10th day. This could be undesirable from the point of view of the increasing exposures to the gastrointestinal tract and bones, as well as leading to possible confusion in interpreting the resultant criteria. Therefore, Graph Four was used in constructing the curve for thyroid doses in Graph Five, except (a) after about the 10th day the intake of fallout material was held to about 11 microcuries, and (b) the first day's fission product activity intake was arbitrarily reduced (as shown in

Graph Five) to lower the doses to the gastrointestinal tract. Thus, having selected the amount of intake of fallout material principally according to thyroid doses, the doses to the gastrointestinal tract and bones were calculated according to Sections I and III and plotted as shown in Graph Five. Then, Graph Four was used (after correction for the first day and after the 10th day as described above) in preparing Table Three for prolonged intake periods by taking the values at the midpoint of these periods, except for the cases where the midpoint fell after about the 10th day when the value was held to 11 microcuries. This selection of activity values at the midpoint of an intake period obviously introduces errors but the uncertainties of times and amounts of intake precludes precise estimations.

V. Discussion

A. Solubility

In calculating doses to the gastrointestinal tract it has been assumed, as the limiting case, that all of the fallout material is insoluble.

The solubility of fallout material varies, depending among other factors upon the surface over which the detonation occurred. The fallout material collected in soil samples at the Nevada Test Site has been quite insoluble, i.e. only a few percent in distilled water and roughly 20-30 percent in 0.1 N HCI. However, it would be expected that the activity actually present in drinking water supplies would be principally in soluble form. The water collected from a well and a cistern on the Island of Rongelap (Table Four) about 21 months after the March 1, 1954 fallout, was found to have about 80 percent of the activity in the filtrate, but there was an undetermined amount that settled to the bottom. Other data suggest the material to have been about 10 percent soluble in water.

In the event contaminated food is ingested it is possible that the total activity--soluble and insoluble--may find its way into the gastrointestinal tract since at times immediately following a fallout most of this activity probably would come from the surface contamination rather than the soil-plant-animal cycle. There may then follow some solubilizing in the acid stomach with subsequent removal from the tract before reaching the lower large intestine. Thus, it would appear that the assumption that ingested activity is associated with insoluble material, presents a limiting and unlikely case, yet probably being well within a factor of two of the actual case.

Of course, if the assumption is accepted that all of the activity is insoluble then there would be no absorption into the body of the isotopes of iodine and of the bone seekers. However, as a limiting case again, it has been assumed that these isotopes are soluble and deposited according to reference five. The great solubility of these iodine isotopes has been observed so that this assumption too is probably well within a factor of two of the actual case.

B. Biological Significance.

After the estimation of radiation doses by any procedure the final step is an evaluation in terms of biological effects both for short and long terms.

1. Gastrointestinal Tract

There have been few experiments where the gastrointestinal tract has been exposed in a manner similar to the one assumed here. One[6] of these fed rats 1.0 to 6.0 millicuries of Yittrium-90 in a single feeding, with four of the 33 animals dying of adenocarcinoma of the colon and additional animals dying with acute and chronic ulceration of the colon. A second group of rats was given 0.46, 0.20, or 0.06 mc of Y^{91} per feeding over a period of three months with total accumulated amounts of 31.2, 15.6 and 4.68 mc respectively. Six of the eight animals at the two higher levels died with carcinoma of the colon and no malignancies were observed at the lowest level. The authors made no estimate of radiation doses.

In another experiment,[7] rats were kept alive by the use of parabiosis or para-aminoproprio phenone either pre or post whole-body irradiation of 700-1000 roentgens. Four of the 21 rats developed tumors along the gastrointestinal tract (one each jejunum, ileum, duodenum, and colon), with four additional animals showing tumors in other organs. Lesser doses have been shown to produce appreciable percentage of intestinal carcinomas in mice by using fast-neutrons, but this is not so applicable to the present discussion of beta exposure.[8] Further, in comparing gastrointestinal irradiation only, versus whole body, the question is raised as to any possible indirect carcinogenic action in the latter case.[9]

One summarizing statement of the short term effects stated, "--- though the gastrointestinal tract is one of the sensitive systems to ionizing radiation, it also has a most remarkable regenerative and reparative capacity. It takes doses of well over a thousand roentgens to permanently damage the gut in most mammals studied, and it is capable of rapid, dramatic recovery of anatomical and functional integrity with doses in the lethal range."[10] Evaluating the data from dogs exposed to whole-body X-radiation the authors said, "--- it is suggested that doses of approximately 1,100 to 1,500 r may represent the upper limit of the possible efficacy of supportive measures in the treatment of the syndrome of acute radiation injury. With greater doses the damage to the intestinal mucosa appears irreparable and of an extent incompatible with life."[11] At the same time, it has been repeatedly indicated that the irradiation of the gastrointestinal tract plays a major role in gross whole-body effects associated with radiation syndrome.[10,11,12,13,14,15,16,17,18, 19] In fact one author[12] summarizes several experimental findings, "In producing acute intestinal radiation death, irradiation of any major portion of the exteriorized small intestine alone is almost equivalent to whole-body irradiation---." Graph Five suggests that the large intestine may receive significantly greater doses than the small intestine or stomach, and available data does not make clear what would be the whole-body effects versus doses delivered in such ratios. Most of these experiments deal with the more violent criteria of death, but they do suggest that the major contributory factor to recognized whole-body effects such as nausea and vomiting associated with whole-body exposures of 100-200 roentgens, may be the result of the gastrointestinal reaction. This, then further suggests that several hundred rads to the lower large intestine together with the lesser exposures to the small intestine and stomach according to Graph Five may be in the range where onset of radiation sickness might occur. Such doses to the lower large intestine might be approaching those that might produce intestinal tumors in a small percent of those so exposed.

2. Thyroid

The treatment of disorders of the thyroid with radioiodine has led to considerable information on doses and their effects to this organ. (Only a partial list of references are noted)[20,21,22,23,24] Whereas these treatments have been principally with abnormal thyroids, much of the information may be extrapolated to normal thyroids for the purposes of this discussion. In addition there are other data based on euthyroid (normal) thyroids in patients suffering such ailments as congestive heart failure.[25]

The picture that is clearly presented is that of the relative insensitiveness of the adult thyroid to radiation. For example, Freedberg, Kurland, and Herman,[25] report "---Seven days after administration of 17 and 20 millicuries of I^{131}, which delivered 14,500 and 31,000 rep, respectively, to the thyroid gland, no histologic changes were noted which could be attributed to I^{131}.--- Fourteen and twenty-four days, respectively, after administration of 59 and 26 millicuries of I^{131}, marked central destruction of the thyroid gland was noted.---" Since the first two patients expired seven days after administration of the I^{131} from pulmonary edema, it does not eliminate the possibility that destructive changes might have appeared in the thyroid if these patients had survived. However, the evidence from other studies strongly indicate that if any pathological effects were to be noted in the thyroid after an exposure of some 10,000 reps they would be minimal. Likewise, the possibility of serious damage to other organs of the body, such as parathyroids and trachea which are simultaneously exposed to the I^{131} radiations, would be exceedingly small.

On long term effects, two summarizing statements may be made. "No thyroid neoplasm was found which could be attributed to I^{131}," [25] after doses to normal thyroids running into many tens of thousands of reps and after periods of observation up to more than eight hundred days. "In a series of over 400 patients treated with radioactive iodine at the Massachusetts General Hospital during the past ten years no known carcinoma of the thyroid attributable to this agent has developed. Definite answers to the question of carcinoma formation must await prolonged observation of treated patients." [23] Here the average treatment dose of I^{131} was 10 millicuries and of I^{130} 25 millicuries.

3. Bones

It is recognized that the intake and deposition of strontium-89 and 90 are intimately associated with the calcium in the diet. Whereas it has been assumed here that a fixed percentage of the strontium intake is deposited in the bones (Reference Five). It is realized that this method involves uncertainties, as would the necessary assumptions to generalize for a wide variety of calcium--strontium ratios and intakes to cover multiple categories. In situations where doses to the bones appear to be the critical criterion (such as later times after detonation than considered here), it would be necessary to make a more precise evaluation.

Unequal distribution of isotopes in the bones has been observed. Thus, the dotted line in Graph Five is included to suggest a possible larger dose to those regions.

Considerable data have been collected on radiation produced bone cancers. One summarizing statement is "--- Visible changes in the skeleton have been reported only after hundreds of rep were accumulated and tumors only after 1,500 or more."[27] When one examines Graph Five and reviews the data on doses and effects to the gastrointestinal tract and possibly children's thyroids, it would appear that doses to the bones is not the critical factor for the times discussed here.

4. Summary

Table Six summarizes some possible biological effects from radiation doses. Due to inherent uncertainties in such analyses together with expected wide biological variances among individuals, Table Six is intended only to suggest a generalized picture of doses versus effects.

The physical calculations of radiation doses above were for adults. For equal intakes of radioactivity, children probably would receive higher exposures due to the smaller organ masses, and in the case of bones a greater deposition would be expected. On the other hand, increased turnover of iodine in children's thyroids might eliminate these isotopes more rapidly and thus reduce the dose. In general, however, it would appear wise to establish lower limits of intake of radioactivity for children.

C. Permissible Intake

It is the amount of intake of a given type of radioactive material that is important, not merely its presence or absence. The preceeding discussion attempted to give estimates of radiation doses resulting from intake of fallout material, together with some possible biological effects. How much intake is actually permitted depends upon many factors including the essentialness of the food and water to sustaining life, and one's philosophy of acceptable biological risks and damage in the face of other possible hazards such as mass evacuation. Table Three gives estimates of the amount of contamination in food and water to produce the radiation doses to the critical organs as shown in Graph Five. With these values in mind, reference may be made to Table Six of possible biological effects from given doses. Command decisions must then be made as to the permitted intake of radioactivity.

Such evaluations as attempted here are necessary and valuable for planning purposes, but once the fallout occurs the emergency of the situation may preclude immediate analysis of the food and water supplies. Further, the abstinence of ingestion of food and water because it might be contaminated could not be continued indefinitely. Therefore, the following three common sense rules are suggested:

1. Reduce the use of contaminated food and water to bare minimum until adequate monitoring can be done; use first any stored clear water and canned or covered foods; wash and scrub any exposed foods and;

2. If the effects of lack of food and water become acute, then use whatever is available but in as limited quantities as possible, and whenever possible make a selection of the least likely contaminated water and/or foodstuffs, and

3. Since it is especially desirable to restrict the intake of radioactivity in children, give them first preference to food and water having the lowest degree of contamination.

One possible evaluation needed in an area of heavy fallout might be the relative hazards from the external gamma exposure versus internal doses from ingestion of the material. (Inhalation is thought to contribute only minor relative doses under the conditions discussed here). One of the best evidences on this, was the fallout that occurred on the Rongelapese in March 1954.

Those in the highest exposure group received 175 roentgens whole body external gamma exposure yet their body burdens of internal emitters were relatively low (Table Five).[28] These and other data suggest that:

> If the degree of contamination of an area for times immediately following a detonation is such that the external gamma exposure would permit normal and continuous occupancy for periods immediately following a fallout, the internal

> hazard would not deny it, (even realizing that the doses from the external gamma radiation are an addition to the internal exposure).

This is based on some reasonable assumptions of (a) 25-50% reduction of gamma exposure afforded by living a part of each day in normal family dwellings, (b) washing and/or scrubbing exposed foods, and (c) excluding areas where relatively little fallout occurred, but into which may be transported highly contaminated food and/or water. After longer periods of time during which the gamma dose rates in an originally highly contaminated area have decreased to acceptable levels, it probably would be necessary to evaluate the residual contamination for the bone seeking radioisotopes, especially strontium-90.

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TABLE ONE

RELATIVE RADIATION DOSES TO GASTROINTESTINAL TRACT, FROM INGESTING INSOLUBLE RADIOACTIVE FALLOUT

	Time After Detonation Intake Occurs		
	1st Hour	1st Day	Limiting Case *
Stomach	1.4	0.086	0.03
Small Intestine	0.39	0.068	0.03
Upper Large Intestine	1.7	0.81	0.49
Lower Large Intestine	1.0	1.0	1.0

*Based on assumption that there is no significant decrease in activity during time of passage through gastrointestinal tract. After a week following a detonation the decrease in activity between the midpoint of time in stomach to midpoint of time in lower large intestine is within 20% of this condition.

TABLE TWO

APPROXIMATE FISSION PRODUCT ACTIVITIES MICROCURIES PER MILLILITER OR GRAM x 10^2 TO PRODUCE ONE RAD DOSE TO LOWER LARGE INTESTINE*

Duration of Ingestion (Days)	Start of Intake (Days after detonation)							
	1 (1st Hour)	2 (24th Hour)	3	4	5	10	15	20
1	25	1.8	1.4	1.2	1.0	0.83	0.81	0.76
2	17	1.2	0.78	0.64	0.58	0.45	0.41	0.38
3	11	0.90	0.59	0.47	0.40	0.30	0.29	0.27
4	9.1	0.73	0.47	0.38	0.33	0.24	0.22	0.21
5	8.3	0.65	0.41	0.32	0.28	0.20	0.18	0.16
10	6.6	0.46	0.29	0.21	0.18	0.12	0.10	0.094
15	5.6	0.38	0.24	0.19	0.15	0.092	0.077	0.070
20	5.4	0.35	0.21	0.15	0.13	0.079	0.064	0.057

* a. Activities computed at start of intake period.

b. Based on intake of 2200 milliliters or grams of water and food per day for adults.

c. Assumes all of the activities are associated with insoluble material.

TABLE THREE

APPROXIMATE FISSION PRODUCT ACTIVITIES MICROCURIES PER MILLILITER OR GRAM x 10^2 TO PRODUCE THE DOSES SHOWN IN GRAPH FIVE

Duration of Ingestion (Days)	Start of Intake (Days after detonation)							
	1 (1st Hour)	2nd (24th Hour)	3rd	4th	5th	10th	15th	20th
1	15	1.5	0.9	0.7	0.6	0.52	0.51	0.51
2	9	0.85	0.5	0.38	0.34	0.28	0.26	0.26
3	5	0.60	0.36	0.28	0.23	0.19	0.19	0.18
4	4	0.50	0.3	0.22	0.19	0.15	0.15	0.14
5	3	0.43	0.23	0.19	0.17	0.13	0.12	0.11
10	2.3	0.30	0.17	0.13	0.11	0.078	0.07	0.065
15	2	0.25	0.15	0.12	0.10	0.060	0.05	0.050
20	2	0.23	0.13	0.098	0.085	0.050	0.044	0.040

* a. Activities computed at start of intake period.

b. Based on intake of 2200 milliliters or grams of water and food per day for adults.

c. Assumes all of the activities are associated with insoluble material for estimating upper limit of doses to gastrointestinal tract, and all of the isotopes of iodine are soluble for estimating upper limit of doses to thyroid.

d. For prolonged periods of intake, the values at the midpoint of the period (Graph Four) were taken as basis for calculations, except for the cases where the midpoint fell after about the 10th day when the value was held to 11 microcuries.

TABLE FOUR

CONCENTRATIONS IN WATER ON ISLANDS IN THE PACIFIC AND ESTIMATED GAMMA DOSE RATES AT D + 1, THREE FEET ABOVE GROUND

Date	Location	Gross Fission Product Activity (d/m/ml)
	Rongelap Island (3.5 roentgens per hour)	
D + 2	Cistern - Rongelap Islands	~50,000 - 75,000
D + 34	" "	~ 5,500
D + 34	Openwell "	~ 2,000
D + 300	Cistern "	~ 3
D + 330	" "	~ 4
D + 600	" "	~ 5.5
D + 600	Open Well "	~ 0.5
D + 600	Cistern " (With collapsed roof)	~ 1.3
	Kabelle Island (19 roentgens per hour)	
D + 330	Ground water	~ 48
	Eniwetok Island (8.5 roentgens per hour)	
D + 330	Cistern	~ 25
	Enibuk Island (1.3 roentgens per hour)	
D + 600	Standing water from can, drum, etc.	~ 1.4

TABLE FIVE

MEAN BODY BURDEN OF RONGELAPESE

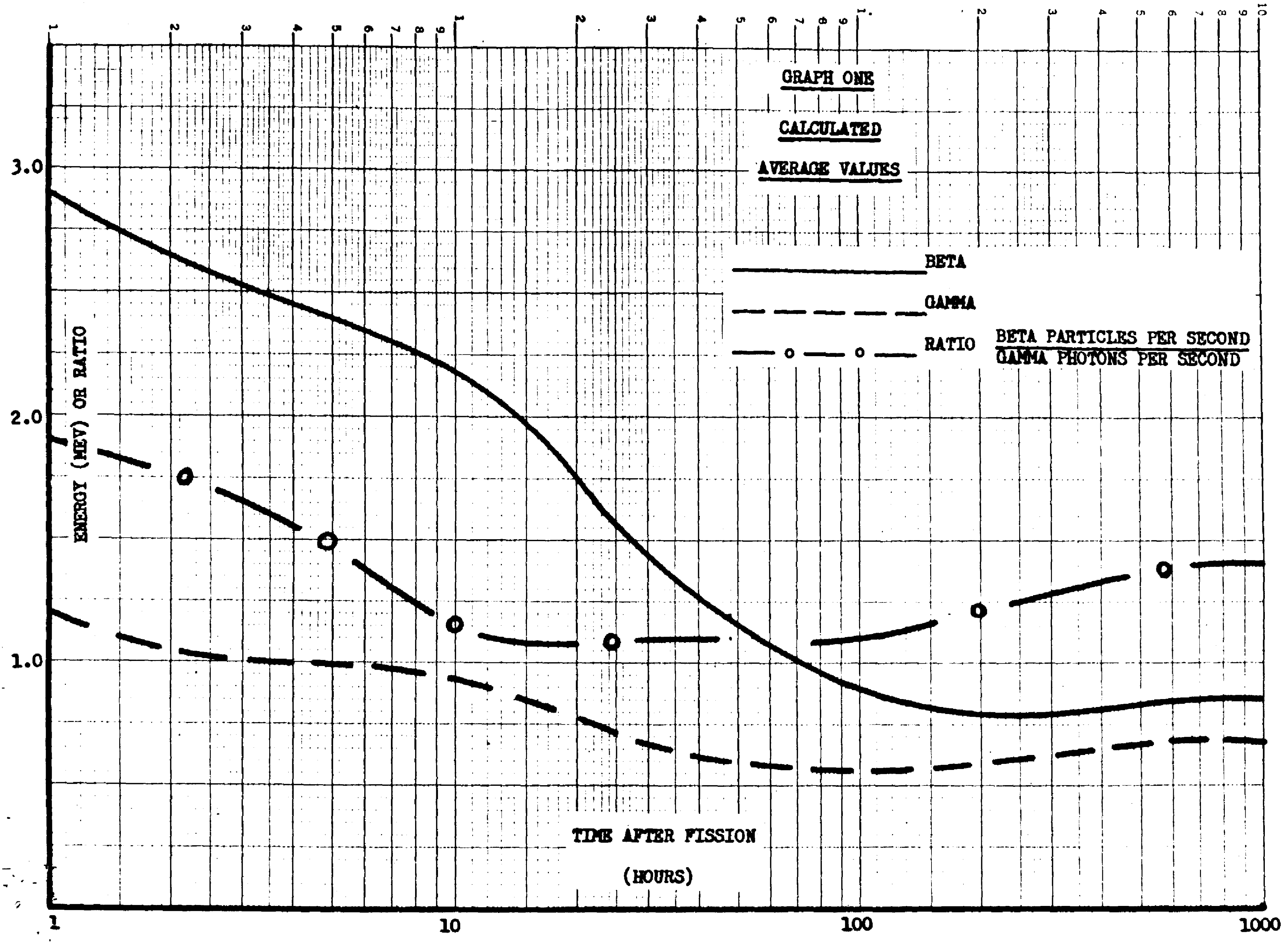
Radioisotopes	Estimated Activity at One Day (μc)
Sr^{89}	1.6 - 22
Ba^{140}	0.34 - 2.7
Rare earth group	1.2
I^{131} (in thyroid)	6.4 - 11.2
Ru^{103}	0.013
Ca^{45}	0.019
Fissile material	0.016 (μgm)

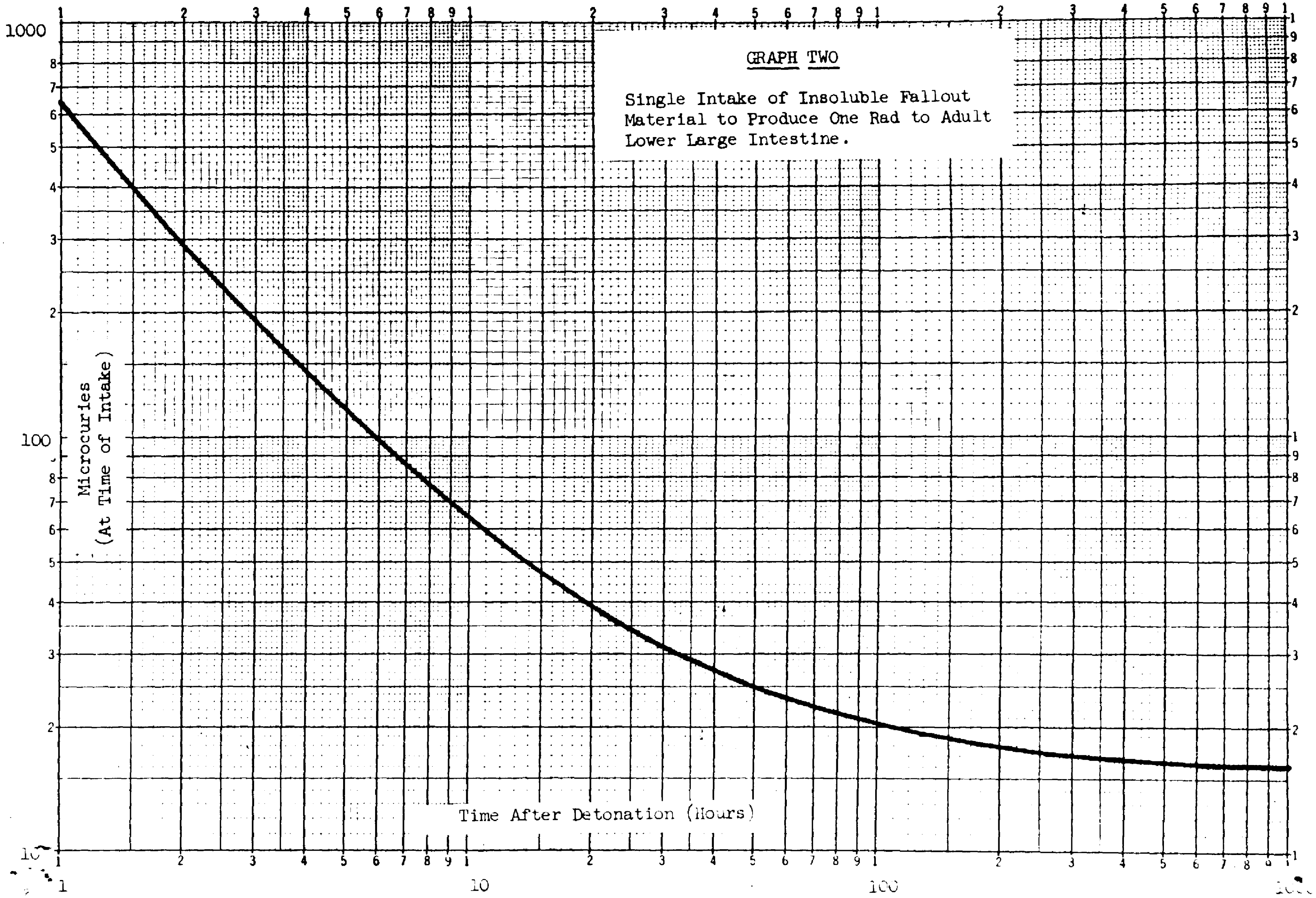
TABLE SIX

SOME POSSIBLE BIOLOGICAL EFFECTS FROM RADIATION DOSES TO SPECIFIC ORGANS *

Dose (Rads)	Gastrointestinal Tract	Thyroid	Bones
10,000		Minor changes in structure	
	Permanent or serious damage ~~or~~ survival threatened		Tumor production
1,000			
	Tumor production		
	Immediate effects such as nausea and vomiting		Minor visual changes in structure
		Potential carcinogenic dose to thyroids of few percent of children and adolescents	
100			

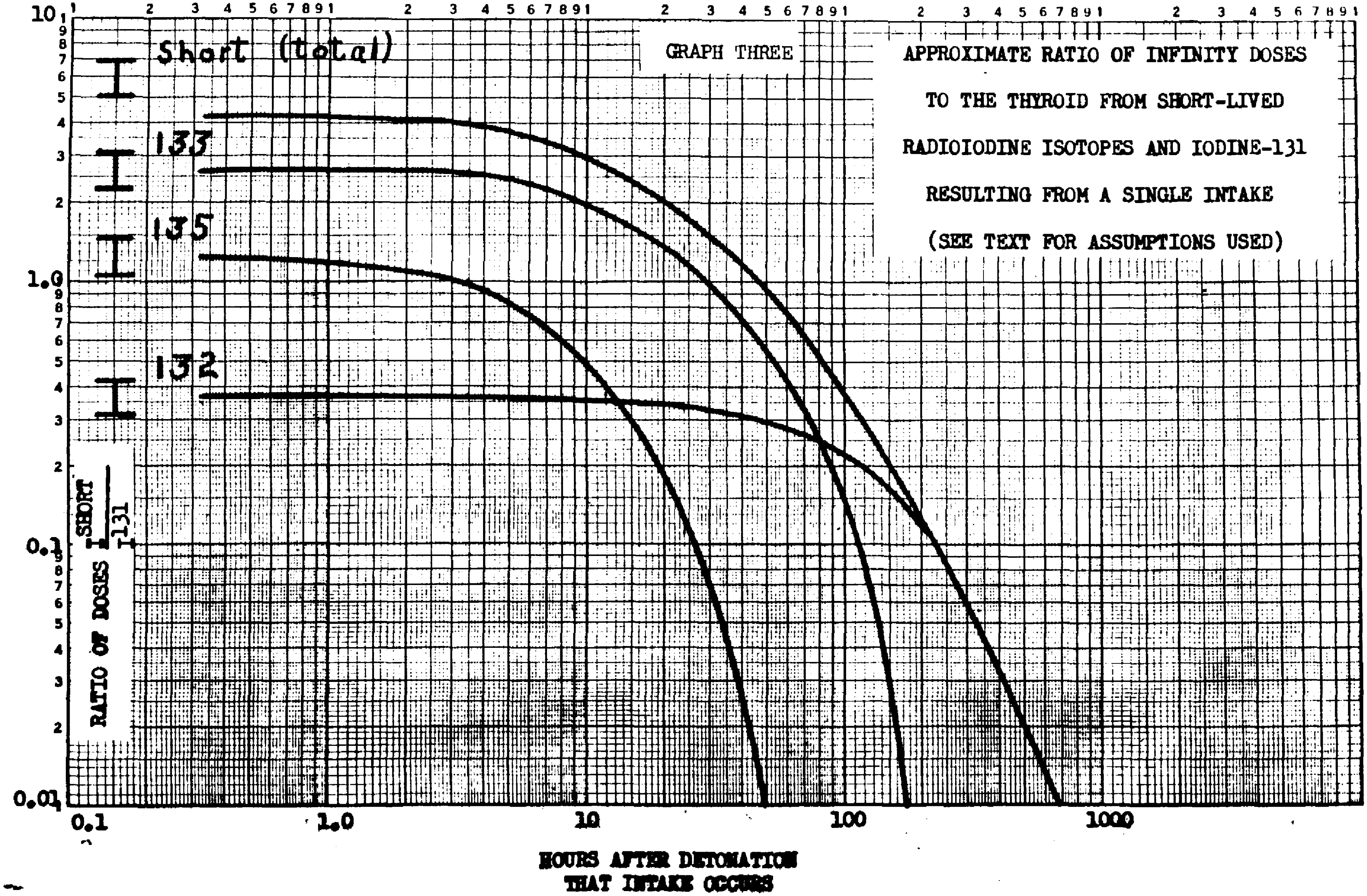
* Lesser short term effects would be expected from the same doses distributed in time.


GRAPH ONE
CALCULATED
AVERAGE VALUES
BETA
GAMMA
RATIO
BETA PARTICLES PER SECOND
GAMMA PHOTONS PER SECOND
ENERGY (MEV) OR RATIO
3.0
2.0
1.0
TIME AFTER FISSION
(HOURS)
1
10
100
1000



GRAPH TWO

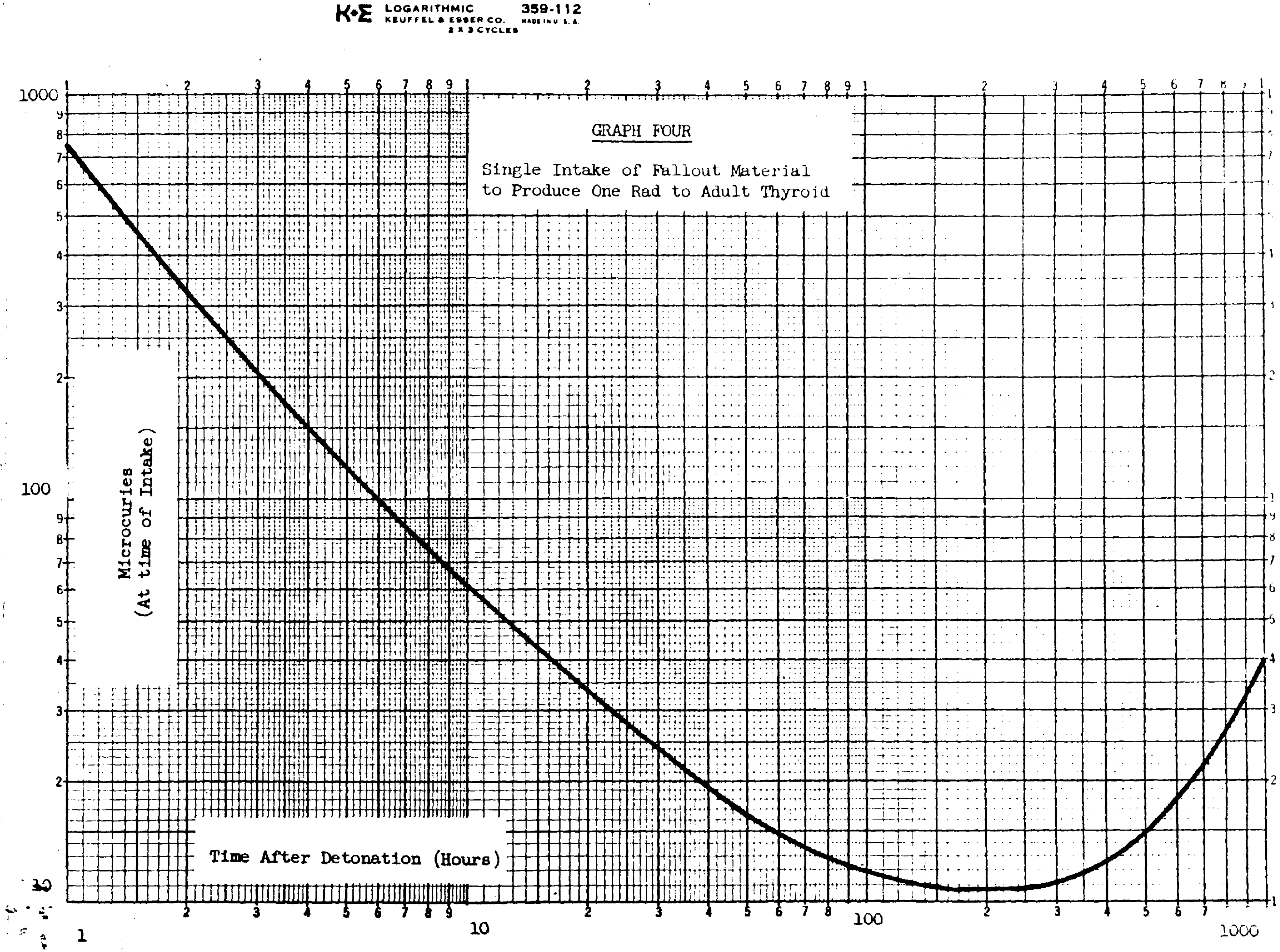
Single Intake of Insoluble Fallout Material to Produce One Rad to Adult Lower Large Intestine.



GRAPH THREE

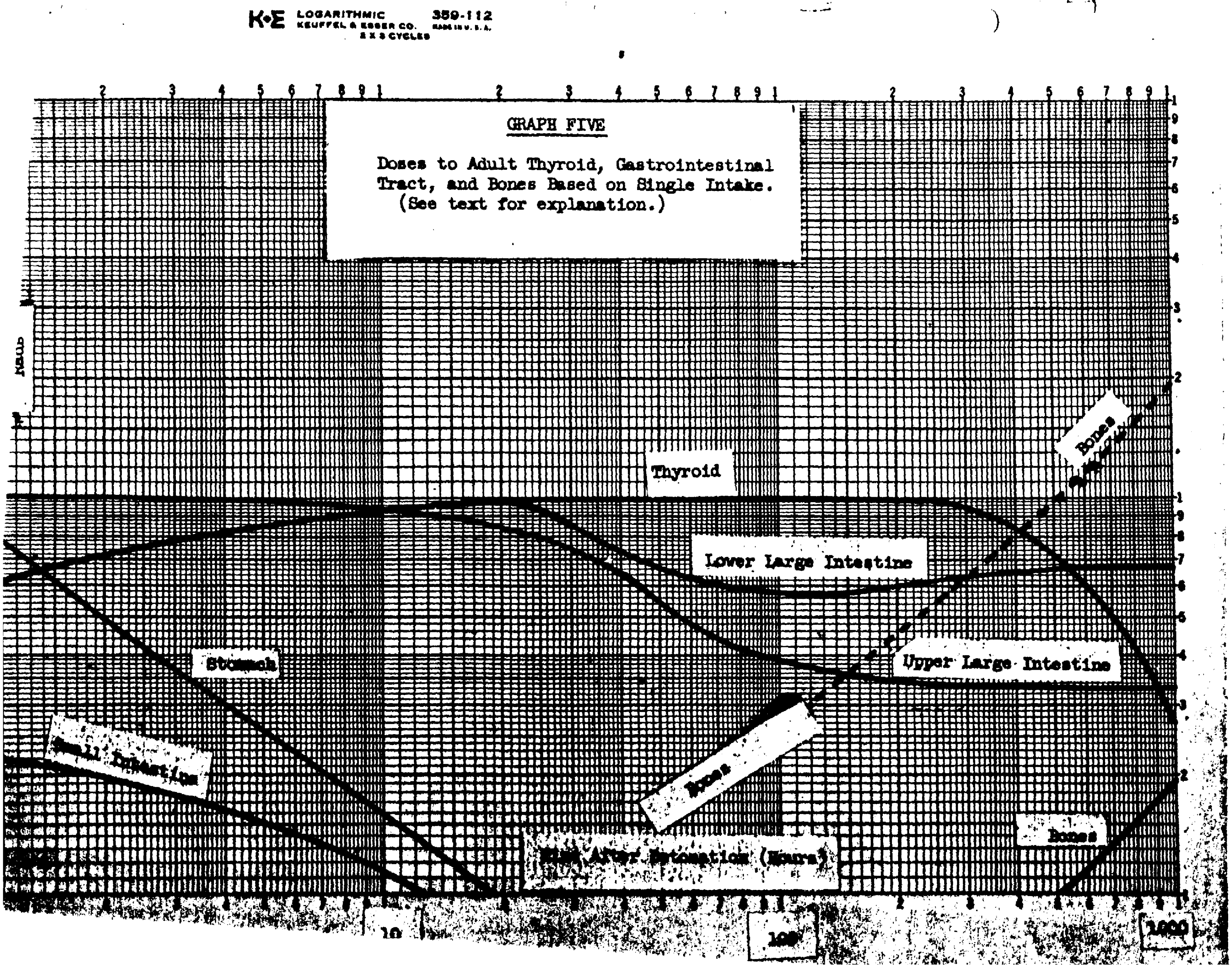
APPROXIMATE RATIO OF INFINITY DOSES TO THE THYROID FROM SHORT-LIVED RADIOIODINE ISOTOPES AND IODINE-131 RESULTING FROM A SINGLE INTAKE

(SEE TEXT FOR ASSUMPTIONS USED)



GRAPH FOUR

Single Intake of Fallout Material to Produce One Rad to Adult Thyroid



GRAPH FIVE

Doses to Adult Thyroid, Gastrointestinal Tract, and Bones Based on Single Intake. (See text for explanation.)

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V. B. 3. Doses to the Bones*

Step 1. Compute the total dose to an organ from a daily intake of constant volume or mass but with the activity intake decreasing according to radiological decay of the isotope.

A. The dose (ignoring for the time any biological decay) to the organ from any day's intake is:

$$D_1 = Ro \int_0^T e^{-\lambda r \tau} \, d\tau - Ro \int_0^{\tau} e^{-\lambda r \tau} \, d\tau$$

Where: D_1 =dose from any day's intake
Ro =initial daily dose rate
λ_r =radiological decay
T =number of days intake
τ =time in days (variable)

$$D_1 = \frac{Ro}{\lambda r} \left(e^{-\lambda_r \tau} - e^{-\lambda_r T} \right)$$

B. The total dose (ignoring biological decay) to the organ is:

$$D_T = \frac{Ro}{\lambda_r} \int_0^T \left(e^{-\lambda_r \tau} - e^{-\lambda_r T} \right) d\tau$$

$$D_T = \frac{Ro}{\lambda r^2} \left[1 - e^{-\lambda_r T} - \lambda_r T e^{-\lambda_r T} \right]$$

C. The dose to the organ considering biological decay is:

$$D_T = \left[\frac{\lambda r}{\lambda_r + \lambda_b} \right] \frac{Ro}{\lambda_r^2} \left[1 - e^{-\lambda_r T} - \lambda_r T e^{-\lambda_r T} \right]$$

$$D_T = \frac{Ro}{(\lambda_r)(\lambda_r + \lambda_b)} \left[1 - e^{-\lambda r T} - \lambda_r T e^{-\lambda_r T} \right]$$

Step 2. Compute initial daily dose rate (Ro):

$(5 \times 10^{-3})(2200)$ = 11μc gross fission product intake on D + 3

$(11)(5.8 \times 10^{-5}) = 6.37 \times 10^{-4}$ μc of Sr^{90} intake on D + 3 *

$(6.37 \times 10^{-4})(0.25) = 1.59 \times 10^{-4}$ μc of Sr^{90} deposited in the bones

$$\frac{(1.59 \times 10^{-4})(\mu c)(3.2 \times 10^{-9})(d/day\text{-}\mu c)(1.0)(Mev)(1.6 \times 10^{-6})\ ergs/mev}{100(ergs/gm - rad)(7 \times 10^{-3})(grams)}$$

1.16×10^{-6} rads/day

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*Under the conditions assumed here, that the water is stored and used as the sole source of supply for 70 years, the strontium-90 content accounts for almost all of the total dose.

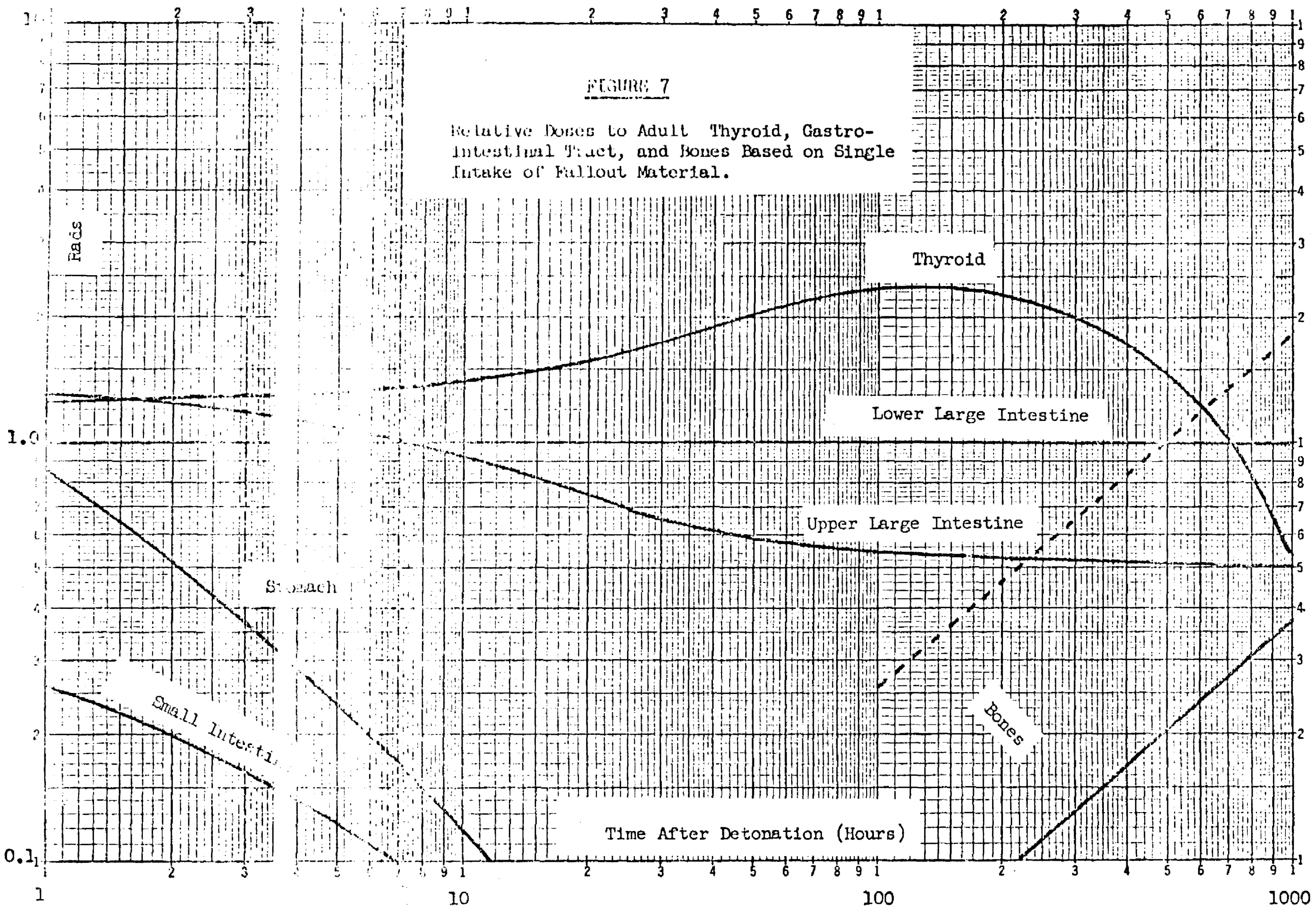

FIGURE 7

Relative Doses to Adult Thyroid, Gastro-Intestinal Tract, and Bones Based on Single Intake of Fallout Material.