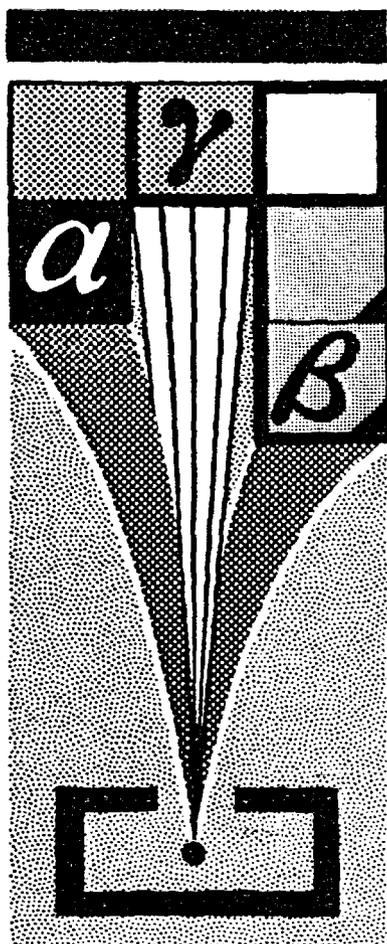


# URANIUM in DENTAL PORCELAIN



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URANIUM  
in  
DENTAL PORCELAIN

By

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September 1976

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE  
Public Health Service  
Food and Drug Administration  
Bureau of Radiological Health  
Rockville, Maryland 20852

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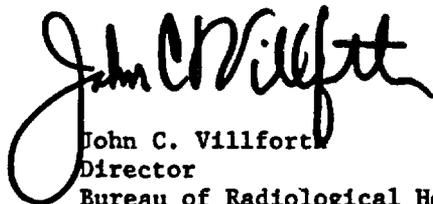
## FOREWORD

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John C. Villfort  
Director  
Bureau of Radiological Health

## PREFACE

For many years porcelains have been employed by dentists to restore missing or defective teeth. Efforts have been made to provide cosmesis in these restorations by simulating the color and appearance of natural teeth. One effective technique has been to add small concentrations of uranium salts for hue and fluorescence in the ceramic tooth. Such additives, once considered to be innocuous, are now under scrutiny as a result of increasing awareness of the potential hazards associated with exposure of large populations to low levels of radiation.

This report on the radiological health aspects of the use of uranium in dental porcelain is based on a study performed by the Bureau of Radiological Health.



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#### ABSTRACT

The radiological health aspects of the use of uranium in dental porcelain are presented. The concentration of uranium is reported for 18 sets of porcelain teeth and 23 samples of porcelain powder. Particle emission rates were obtained for uranium and for the potassium-40 also present in the teeth. These data are used to calculate the annual doses to the individuals who wear porcelain prostheses and to persons who are occupationally exposed to the teeth and powders. Dose modifying factors are discussed for both alpha and beta particle exposures.

Recommendations are presented regarding substitution of nonradioactive agents and interim guidelines on the maximum permissible concentration of uranium in dental porcelain.

#### ACKNOWLEDGMENTS

The author wishes to acknowledge the cooperation and assistance of Dr. Ray Alcox, Dr. John Glenn, Dr. Orlen Johnson, Dr. Frank Lundin, Mr. Frederick Shuman, Mr. Robert Simpson, Dr. Darryl Singleton, Dr. Richard Smith, and the manufacturers and distributors who voluntarily participated in this study.

## INTRODUCTION

Natural teeth have the property of fluorescing under conditions of daylight, tungsten, or ultraviolet illumination. The mechanism involved in the reaction is unknown though it is thought that both protein and inorganic components participate (1-5). In an attempt to match natural coloring and fluorescence, the manufacturers of artificial teeth have added uranium salts to porcelain for over half a century (6). No other substance has been found to imitate the broad spectrum of natural fluorescence. Interest in the fluorescence aspects was particularly intensified after 1950 when high intensity light sources, mercury vapor lamps, and discotheque ultraviolet lamps became widely used.

The amount of uranium additive has always been only a few percent of the total mass of the tooth so that when the U.S. Atomic Energy Commission (AEC) in the 1960's set an upper limit of 0.05 percent by weight for license-exempt use in ceramics, U.S. manufacturers were able to comply (7). This condition for exemption from regulation was not based on an appraisal of the use of ceramics in dental prostheses but rather was an arbitrary value representing the concentration of uranium in ore which would not be practicable to process for nuclear source material. At about the same time the AEC made available depleted uranium at a price that was competitive with natural ores. Dental manufacturers applied for and were licensed to use the depleted material (8). It should be noted that ceramics is generally considered to include such items as dishware, pottery, and tiles. Although the dental prosthetic industry sales volume is very large, the amount of uranium consumed is only a few hundred pounds a year. In fact, none of the domestic manufacturers are currently licensed, but instead purchase license-exempt quantities, i.e., no more than 15 pounds at a time, no more than 150 pounds in a year.

## CURRENT REGULATIONS AND RECOMMENDATIONS

The conditions for license-exempt use of uranium in ceramics as previously stated by the Atomic Energy Commission are still in effect under its successor, the Nuclear Regulatory Commission. The Code permits the receipt, possession, use, transfer, delivery, or import into or export from the United States of source material in any chemical mixture, compound solution or alloy in which the source material is by weight less than one-twentieth of one percent (0.05%) of the mixture, compound, solution, or alloy (7). Source material is defined as uranium, thorium, or any combination thereof....

The U.S. Food and Drug Administration may classify a device either as: subject to controls over labeling and branding; subject to performance standards to assure safety and effectiveness; or, subject to premarket approval (9). A device that cannot be shown to be safe and effective, or for which adequate precautions are not indicated, is not deemed to be properly labeled. Devices for which existing controls are insufficient and for which there is sufficient information for performance standards may be categorized accordingly. Premarket approval may be required for devices having life sustaining functions or potential unreasonable risk for illness or injury.

The Occupational Safety and Health Administration (OSHA) of the U.S. Department of Labor has set occupational exposure limits at 18.75 rem per calendar quarter

for the hands and forearms. The skin of the whole body is restricted to 7.5 rem for the same interval. Dose limits are also established for other organs and the whole body (10).

The International Commission on Radiological Protection (ICRP) has published recommendations on the limits of absorbed dose for the general public and to occupationally exposed individuals (11,12). Relevant dose limits for members of the public are set at 3 rem in a year to the skin and 1.5 rem in a year to single organs not otherwise specified. Adults exposed in the course of their work are limited to 75 rem in a year to hands and forearms, 30 rem in a year to the skin elsewhere on the body.

The National Council on Radiation Protection and Measurements (NCRP) has recommended a dose limit of 0.5 rem in any one year for the public in regard to critical organs (whole body) (13). They permit exceptions where this limit may be exceeded and cite as an example: an alpha-emitting substance in the midplane of the horny layer of skin may be judged to be innocuous. Elsewhere, in this same publication, they note that the skin normally has a mass thickness of 7 mg per cm<sup>2</sup>.

Dose limits for occupational exposure have been set by the National Council at 75 rem in any one year for the hands, 30 rem to forearms and 15 rem to skin other than the hands and forearms. Maximum permissible concentration of natural uranium in air for a 40-hour week is set at  $6 \times 10^{-11}$   $\mu\text{Ci/cc}$  (46).

#### DENTAL PORCELAIN APPLICATIONS

Dental porcelain is used to manufacture artificial teeth for use in full and partial dentures, facings for fixed and removable bridgework, and veneer material for custom fabrication of crowns and bridges. Other materials have also been employed in the production of artificial teeth and crowns such as methacrylate polymers, vinyl resins, and polycarbonates; however, uranium salts are not used with any substance other than porcelain.

A porcelain tooth is constructed of a baked base and one or more covering layers which give the product the desired shading and finish. The compositions of the porcelain powders used vary as does the uranium concentration. The completed tooth is then fired at a high temperature to produce a surface glaze. One or more teeth are held in position in the mouth either by metal clasps attached to adjacent natural teeth or by embedment in a base material that fits the gingival surface.

Crowns are often constructed by fitting a thin metal coping over the damaged tooth. When the coping has been formed to the required dimensions it is removed, covered with a paste of porcelain powder and oven fired to form a hard ceramic finish. A porcelain crown may also be applied directly to a natural tooth without the metal coping.

#### DENTAL PORCELAIN MARKET

Dental porcelain is produced in the United States by four domestic manufacturers and is also imported from several foreign suppliers. Finished teeth are sold in a variety of molds, sizes, and shades of color with the number of combinations running into the hundreds. It is estimated that about 100 million artificial teeth are sold in the United States each year with possibly two to three times that number in storage at the suppliers, dental laboratories, and local practitioner's offices. At least several million are returned to the

manufacturer each year for cash or credit. Teeth are sometimes purchased for investment purposes since, if not used, they may be redeemed for the current market value. It is not uncommon to have teeth returned 10 or 20 years after manufacture.

In addition, porcelain powder is sold to dental laboratories and operatories in sufficient quantities each year to permit the construction of millions of custom-molded crowns.

#### POPULATION AT RISK

According to the National Center for Health Statistics, an estimated 22.6 million persons in the United States in 1971 had lost all their natural teeth (14). Of these, 19.5 million were 45 years of age or older. Over a million edentulous persons did not yet possess any dentures and 686,000 had partial dentures. Women constitute about 58 percent of denture wearers.

Of the population who were not edentulous, an estimated 45 million had lost at least one natural tooth, of which 20 million had replaced the loss with a partial denture (15). Another 60 million persons had teeth restored with crowns.

In summary, up to 100 million persons in this country wear a dental prosthesis, of which approximately half are made of porcelain, and presumably contain uranium. Although dentures, in adults, sometimes serve for the lifetime of the individual, three out of ten edentulous persons require relining or construction of new dentures according to the Center's survey. Data are not available on the actual replacement rate for prostheses in edentulous or other persons.

Occupational exposure occurs during the manufacture of teeth and powder and in the construction and fitting of crowns, bridges and dentures. The number who may be exposed in this manner is estimated to be 15,000 to 20,000 persons.

#### ANATOMICAL STRUCTURES AT RISK

Three soft tissues of the oral cavity are potentially exposed to particulate radiation from artificial teeth. These are the gingivae (gums), buccal parietes (inner cheek and lips) and lingua (tongue). Crowned teeth or natural teeth adjacent to an artificial tooth are also subject to short-range irradiation; however, the thickness of the dentine and enamel and relative insensitivity of the cells and fibres of the tooth leave the basal cells of the oral mucosa to be considered as the critical organ. The basal layer occurs immediately below the surface or epithelial cell layer.

The organs to consider in occupational exposure would be the fingers, the digestive tract (accidental ingestion), and the lungs and lymphatic system (inhalation of powders).

The emissions of uranium and its daughters will be discussed in greater detail in the dosimetric portions of this report, but it should be mentioned here that alpha, beta, and other particles and photons are present. The first two represent the bulk of the source of ionizing energy, and their penetrability establishes the principal hazards. Alpha particles only have a tissue range of 30 microns or  $3 \text{ mg/cm}^2$ , while beta can reach 200 microns with ease.

O'Riordan and Hunt in their review of radioactive fluorescers note that various authors have reported the thickness of the superficial cells of the buccolabial and gingival tissue to be about 20 mg/cm<sup>2</sup> (or 200 microns) (16). They assume a value of 10 mg/cm<sup>2</sup> (100 microns) as a reasonable estimate for the tongue surface. Wentz, et al. measured the attached gingiva (adhering to the tooth) and reported a three-fold difference in the average epithelial thickness (17). They observed that the width appeared to be age dependent, with older persons more frequently in the thinner range having an average of 7.5 mg/cm<sup>2</sup> (75 microns). Young individuals were more often classified as thick (average 22.5 mg/cm<sup>2</sup>) or medium (average 15 mg/cm<sup>2</sup>).

More recently Whitton (18), using a technique devised by Southwood (19), published values for skin epidermal thickness showing that it is not age dependent, but rather dependent on body site. Whitton states that measurements prior to 1973 were mostly inadequate for radiation protection purposes partly because the inherent elasticity of the skin was not compensated for in the experimental technique. New values for the tissues of the head and neck were given as 4 mg/cm<sup>2</sup> on the average with about 33 percent lying between 2 and 4 mg/cm<sup>2</sup> and 3 percent less than 2 mg/cm<sup>2</sup>. Epidermal thickness of fingers averaged 24 mg/cm<sup>2</sup>, and finger tips averaged 40 mg/cm<sup>2</sup>, with a minimum of 16 mg/cm<sup>2</sup>.

Schoenfeld has commented that Whitton's results were based on a calibration of tissues obtained from post-mortem samples and do not necessarily reflect the amount of stretching which occurred in his samples of living tissue (20). Whitton relates that Southwood made such a comparison, between post-mortem samples and tissue obtained at surgery, and found the calibration factors to be the same.

More significant is Schoenfeld's criticism that the measurements which were made on exterior facial skin do not necessarily apply to the oral mucosa. Consequently, while the values for oral tissues reported earlier may not be in error, they do require affirmation.

#### INCIDENCE OF ORAL CANCER

The major somatic injury to be expected from irradiation of the oral tissue is cancer that may arise from damage to the basal cell layer. Over 90 percent of malignant tumors of the oral cavity are of the squamous cell or epidermoid type, originating in the surface epithelium (21). More common sites are the floor of the mouth, the sides of the tongue, and the faucial arch. Only one of these three sites, the side of the tongue, may be in direct contact with dental porcelain. Tiecke and Bernier found that 52 percent of oral cancer originated on the tongue (22). The 1975 estimate of the incidence of oral cancers indicates that the tongue is the principal site (23).

Established factors or co-factors in the etiology of oral cancer are syphilis, chronic alcoholism, smoking and chewing tobacco (21). Overall incidence of oral cancer is estimated to be 16,900 new cases per year, not including the pharynx, or about 3 percent of all cancers. Age of onset is typically in the later decades with males more than twice as susceptible as females. Lack of a gross association between sex, dentures and cancer does not argue against causality but rather against a single factor causation or possibly that rates of cancer adjacent to teeth are not available by sex and denture wearing status.

## RADIATION AND ORAL CANCER

The tissues of the oral cavity are not particularly radiosensitive and the induction of malignant lesions has only been causally related to therapeutic doses (21). On the other hand, the carcinogenic properties of low level chronic radiation are not well known and have not been demonstrated. Extrapolation to low levels of the linear relationship between doses and cancer induction at high levels is a common and heretofore accepted practice as a conservative approach to developing risk estimates for radiation protection guidelines. In words of caution, the National Academy of Sciences in the 1972 BEIR Report (pg. 89) states that such "estimates of mortality from radiation exposure may be too high or too low, for a variety of reasons" (24). Further, on page 96, the Report says "there are cogent radiobiological reasons for doubting that the dose-incidence relationship for cancer in man does, in fact, remain constant in the face of such changes (i.e., doses and dose rates), one of which is the widespread occurrence of repair of most other types of radiation injury at low doses and dose rates, particularly in the case of low-LET radiations." (LET refers to the release of energy per unit distance or linear-energy-transfer.) Consequently, the carcinogenic effects of the low-LET, low dose rate flux of beta particles in the case of uranium in porcelain are questionable. To further complicate the evaluation, while low-LET radiation tends to decrease its effectiveness with a decrease in dose and dose rate, the effectiveness of high-LET radiation, such as alpha, can be expected to decrease little if at all with decrease in dose and dose rate (BEIR pg. 88, also Ref. 53). The latter is most significant since, if alpha particles are reaching the basal layer, the energy deposited by them is several times higher than that from beta particles. In this respect some support for Whitton's contention that the basal layer is sometimes within the range of alpha's is the observation by Witten et al., that erythema can be produced by alpha sources (25). It has also been noted that the epidermal surface in the oral cavity may occasionally be eroded by infection or trauma, thus directly baring the mitotic cells to the alpha flux (26).

### PREVIOUS STUDIES ON URANIUM IN DENTAL PORCELAIN

A number of researchers have investigated the potential hazards of irradiation from uranium teeth. The Bureau of Foods, Food and Drug Administration, in 1967 estimated that the doses from sets of dentures containing natural uranium were 13-16 percent of the maximum permissible dose and recommended "that the unnecessary use of radioactivity in teeth be discouraged" (27).

Nally and co-workers, in 1969, in Geneva, reviewed the products of one prominent manufacturer (28). The dose to patients exceeded the legal radiation limits, but in the authors' opinion did not constitute a hazard. They did warn against accidental ingestion of the powder by dental ceramists.

Moore and MacCulloch, in 1974, tested some teeth and powders available in Great Britain (29). Based on beta particle measurements they arrived at a dose estimation of about 0.45 rem/year, which they stated was "well within the acceptable limit for persons who are not exposed by the nature of their occupations to extra radiation." They also cautioned against accidental ingestion in the manufacture of powder and the fabrication of teeth and crowns.

Other researchers have noted the presence of uranium or emission of particles (30-33) with the most comprehensive report being that written by O'Riordan and Hunt and issued as the National Radiological Protection Board Report No. 25 (16). They analyzed 20 powders (five brands) and anterior specimens of teeth

for three brands. Their dose estimates are based on the highest uranium concentration noted (in two powders) which was 1,000 ppm or 0.10 percent by weight. Annual alpha doses at the interface with tissue were calculated to be 589 rem, beta were 2.8 rem. The alpha dose at 3 mg/cm<sup>2</sup> depth was calculated to be zero, with beta decreasing only to 2.7 rem. These dose values were based on the assumption of constant contact between porcelain and oral mucosa. Their calculations were supported by G-M counter, film, TLD, and silicon detector measurements. Doses from photons and other particles of uranium decay were insignificant, but an annual dose of 0.23 rem from the natural potassium-40 content of porcelain was reported.

In their assessment, the authors dismissed alpha doses on the basis that the particles did not penetrate to the basal cell layer. They recommended that, based on the dose due to beta, the use of radioactive fluorescers in dental porcelain be discontinued. As regards the hazard of ingestion they estimated that technicians could ingest 300 grams of powder weekly without exceeding their limit. External radiation dose was no cause for concern because of the short exposure periods for technicians or staffs of dental materials companies.

#### IRRADIATION OF THE MUCOSA BY NATURAL SOURCES

The oral mucosa is subject to irradiation from a number of naturally occurring sources. Potassium-40, carbon-14, and other trace nuclides can be found in all living tissues, though not necessarily in the same ratio to stable nuclides as they occur in the environment. Even uranium has been identified in natural teeth (34). Several studies have been published on the activity of radium-226 and lead-210 in human teeth. The results are summarized by Lovaas and Hursh, who found femtocurie ( $10^{-15}$ ) levels of both nuclides in their own samples (35). Based on their mean values, the annual dose to the mucosa from alpha particles would be about 3 mrem, and from beta would be about 0.1 mrem. The total dose to the oral mucosa from all internal and external sources has been estimated to be about 0.1 rem on an annual basis (36).

Another source of radiation is the accumulated products of nuclear testing fallout. Although those may not have been natural in origin, they presently exist in and will continue to be part of the environment. One product which is found in teeth is the beta emitting nuclide strontium-90. The element is incorporated in the permanent teeth at a rate determined by the dietary intake. Rosenthal found that the concentration during a 5-year growth period rose to about 3 picocuries ( $10^{-12}$ ) per gram of calcium present (37). If this were to become the equilibrium level, it would indicate an annual dose of about 0.7 mrem.

#### SAMPLE COLLECTION

The Bureau of Radiological Health, FDA, contacted 28 manufacturers and distributors of dental products and requested samples of porcelain teeth and powders. Seven companies did submit samples, two others stated that they did not use uranium in any product, and three were reported out of business. Thirteen failed to respond at all. Fortunately, those firms which did cooperate include the major suppliers, and therefore this survey may be fairly representative of the market.

Eighteen sets of teeth were available for analysis, one containing natural uranium, the others containing varying amounts of depleted uranium. Data on the specified uranium content were also submitted for most samples.

Twenty-three powders were originally collected along with a set of crowns provided by one respondent. Twenty other samples of powder were made available during the study but are not included in the present report.

The molds and shades included in the samples are among the most popular in present use.

A large number of permanent teeth were provided by Dr. Carl E. Anderson, Professor of Biochemistry, of the University of North Carolina.

#### ANALYSES FOR URANIUM CONCENTRATION

The gamma spectra of samples of natural and artificial teeth and porcelain powders were scanned with an Ortec WIN <sup>15</sup> GeLi detector coupled to a Nuclear Data model 4410 multichannel analyzer. Uranium was identified in artificial teeth by x-ray emissions at 63 and 93 keV. Potassium-40 was evident in all scanned samples by the gamma emission at 1.46 MeV. Traces of thorium-232 were noted in a few artificial teeth.

Porcelain teeth and powders were analyzed for uranium content by gamma counting techniques. Samples were centered on a 4 x 4 inch sodium iodide (Tl) detector (Harshaw 16 MBS 16/3E). High voltage was obtained from a Hewlett Packard power supply, Model 6515A. The spectra were accumulated on a 400 channel analyzer (Technical Measurement Corp., Model 402) generally for periods ranging from 4 hours to 24 hours, with a few low-level samples measured as long as 72 hours.

Net counts were integrated at the 93 keV peak of the uranium daughter thorium-234 and compared to a 1.0 gram sample of depleted uranium obtained from the National Bureau of Standards (Standard Reference Material, U-0002). A sample of potassium chloride salt was used to determine the potential interference at 93 keV from the potassium-40 present in porcelain. Similarly, the potential contribution from thorium-232 was measured, since trace amounts were detected in some teeth. In practice the algorithms for subtracting the counts due to potassium-40 and thorium-232 were not required, since the amounts present contributed far fewer counts to the 93 keV peak than were observed in the standard deviation for the net uranium count.

The results of the analyses are listed in Table 1 for teeth and powders. The manufacturers' specifications on the uranium content of teeth were available for 12 samples, each of which was consistent with the measured concentration. Data on powder analyses were similarly compared with the supplier's specification for 14 samples. For powders, three samples differed by a factor of two, one by a factor of five but the rest were relatively consistent. Two powders exceeded the license exempt level of 0.050 percent concentration, and exceeded the manufacturer's specification as well. Whether these two were isolated incidences of poor processing or an indication of a general lack of quality control is not known. Duplicate samples from the supplier (from the same batches?) confirm the over-limit values. Since two or more powders are used to construct a tooth, the final product would not necessarily have an effective concentration above 0.050 percent by weight.

Uranium concentrations in powder samples A, D, and L were also verified by counting on the Ortec/Nuclear Data system, then recounting after addition of a known amount of natural uranium oxide (NBS -SRM 950a).

Table 1. Uranium concentration in dental porcelain

Porcelain Teeth		Porcelain Powders	
SAMPLE NO.	PERCENT URANIUM	SAMPLE NO.	PERCENT URANIUM
1	0.030	A	0.040
2	0.037	B	(a)
3	0.017	C	0.019
4	0.019	D	0.099
5	0.037	E	0.013
6	0.001	F	0.023
7	0.044	G	0.006
8	<0.001	H	0.003
9	0.007	I	0.017
10	0.037	J	0.027
11	0.003	K	0.025
12	0.020	L	0.053
13	0.044	M	0.027
14	0.028	N	0.002
15	0.008	O	0.035
16	0.025	P	0.019
17	0.037	Q	0.028
18	0.003	R	0.007
		S	0.038
		T	(a)
		U	(a)
		V	0.022
		W	0.017

(a) Sample too small to yield significant count rate over background.

## PARTICLE EMISSION RATES

The largest incisor or molar in each set was selected for measurement of the particulate emission rates. The samples were embedded in Styrofoam in a steel planchet with the surface exposed which would normally be in contact with the buccal tissue. The Styrofoam was covered with aluminum foil to provide a conductive medium around the tooth. The area of the exposed surface of each sample was measured with a millimeter scale to permit calculation of the flux per unit area. In some instances an aluminum mask was placed over the sample to define the alpha emitting area. Because of the irregular contours of the teeth, both the measurement and masking techniques only provided a first approximation to the actual exposed area, though the results for both methods were comparable.

Counting was performed in a Nuclear Measurements Corporation Proportional Counter, Model PC-3A, using P-10 gas. Counting periods were from 6 hours to 24 hours for alpha emission and 1 hour for beta emission. The chamber efficiency was measured with a Radium D-E source, Model RT 5 (Nuclear-Chicago) and found to be 97 percent.

The mass of the molar specimens was determined by cleaning the samples of the mounting wax, then weighing on an analytical balance. Anterior teeth, however, are constructed with one or two gold pins protruding from the rear. The pins are difficult to extract without literally powdering the tooth. In one case, though, the pin fell out just in removing the tooth from the mounting wax. Seven other pins were removed by brute force. The weight of each pin was very close to 0.015 g. This mean value was used to correct for the mass of the pins in weighing all of the anterior teeth.

The results of the alpha and beta measurements are listed in Table 2 and Table 3. For comparison the theoretical alpha emission rate,  $N_0$ , per unit area, A can be calculated as:

$$N_0 = \frac{NRA}{4}$$

where N is the number of particles emitted per unit time per unit volume when the particle has a range, R (38). The range was obtained using the Bragg - Kleeman relationship:

$$R = R_0 (w/w_0)^{1/2}$$

where  $R_0$  is the range in an element of atomic mass  $w_0$ , and  $w$  is the effective mass of the medium. The ratio  $w/w_0$  is selected to be close to unity. For simplicity, porcelain was assumed to be pure silicon dioxide, though it usually also contains oxides of aluminum, calcium, sodium, potassium, and magnesium. The effective mass was computed by the method of Evans (39). The isotopic composition of depleted uranium was assumed to be that cited in the National Radiological Protection Board Report 25 as typical (16). The range for aluminum was selected from the Stopping-Power Tables as approximate to porcelain (41). The calculated value of  $N_0$  for Sample No. 13 (the highest flux from a depleted uranium sample) was 52.1 alpha's per hour per unit area, a remarkable coincidence to the measured value in view of the many assumptions. The manufacturer's specifications usually cite the enamel or surface powder as containing a lower concentration than the body powder, whereas theoretical fluxes are based on the effective concentration for the whole tooth. Thus, it would be expected that observed count rates would reflect surface concentrations and be lower than calculated values in such samples.

Table 2. Alpha particle emission from porcelain teeth

Sample number	Net count per hour	Count/hr per gram	Count/hr per cm <sup>2</sup>
1	15.2	25.6	21.3
2	24.7	42.3	41.5
3	5.6	9.2	7.8
4	7.0	10.5	9.0
5	24.4	34.7	43.6
6	<0.1	<0.1	<0.1
7	25.1	35.2	51.2
8	1.5	3.4	2.7
9	1.2	2.2	1.8
10	24.8	41.3	34.7
11	6.7	14.0	9.4
12	15.0	22.7	22.7
13	35.2	55.2	52.1
14	39.2	57.2	70.0
15	12.2	22.4	17.1
16	15.8	30.2	26.1
17	38.1	48.6	49.8
18	9.6	15.9	13.3
19 <sup>a</sup>	4.7	--	6.5
20 <sup>a</sup>	<0.1	--	<0.1

a Crown

Table 3. Beta particle emission from porcelain teeth

Sample number	Net count per hour	Count/hr per gram	Count/hr per cm <sup>2</sup>
1	1800	3030	2517
2	1988	3404	3341
3	1281	2103	1792
4	1356	2033	1738
5	2232	3170	3986
6	620	849	795
7	2400	3361	4898
8	389	876	720
9	620	1123	954
10	2004	3334	2803
11	554	1161	775
12	1470	2221	2227
13	2370	3715	3511
14	2009	2933	3588
15	880	1615	1231
16	1589	3032	2626
17	2474	3156	3234
18	729	1207	1013
19 <sup>a</sup>	884	--	1228
20 <sup>a</sup>	0	--	0

a Crown

The alpha emission per gram is plotted in figure 1 against the uranium concentration for each of the teeth. There is a dependency, but for the reasons just noted the correlation is not very high.

The beta emission per gram is plotted versus the uranium concentration for each sample in figure 2. The correlation is higher in this instance reflecting the greater penetrating power of the abundant high-energy beta particles. The intercept obtained from a least squares calculation does not occur at the origin but rather at about 972 betas per gram indicating a rather substantial contribution of particles from a source other than uranium. Since potassium-40 is the only radioactive nuclide also present in every sample, it can be assumed that this is the co-emitter.

The integrated net counts at the 1.46 Mev gamma peak of potassium-40 were obtained for each sample. The gamma counts per gram varied by a factor of two over the whole set of samples. The distribution was not random but appeared to reflect the feldspar composition of porcelain in the country of origin. Data are given in Table 4.

Table 4. Gamma counts per gram per hour at 1.46 MeV for dental porcelain samples

Domestic		Imported
148	136	111
136	159	115
134	145	132
133	139	119
152	166	71
146	162	

#### THERMOLUMINESCENT DOSIMETER MEASUREMENTS

An attempt was made to evaluate the alpha and beta fluxes by exposure of thermoluminescent lithium fluoride chips (TLD-100). The dosimeters (TLDs) were approximately 3 x 3 mm and 0.2 mm thick. The same teeth that were previously counted in the proportional counter were selected for the alpha exposure studies. The samples were partially embedded in a Styrofoam block and TLDs were centered directly on the exposed faces. An additional six teeth were mounted in another block to monitor beta exposures. These latter samples were overlaid with Mylar film having an attenuation equivalent to 6 mg/cm<sup>2</sup> thus preventing the alpha particles from reaching the dosimeters.

A plutonium-239 source (Eberline Instrument Corporation, P-350) was used to provide calibration for alpha-exposed TLD's and a depleted uranium source (Eberline Instrument Corporation) served to calibrate for beta-exposed TLD's. The respective exposure periods were 1 week and 11 weeks. All samples, calibration and background dosimeters were readout on the same date. For all TLD's the surface which was in contact with the radioactive source was turned to face the photomultiplier tube in the readout chamber in order to reduce absorption effects.

Evaluation of the alpha calibrated dosimeters indicated that the exposure period had been too brief and that the recorded counts for the 1-week samples were necessarily only due to beta particles. The six teeth exposed to beta for 11 weeks gave results consistent with their parallel 1-week exposures,

FIGURE 1

Alpha Emission Rate vs Uranium Concentration

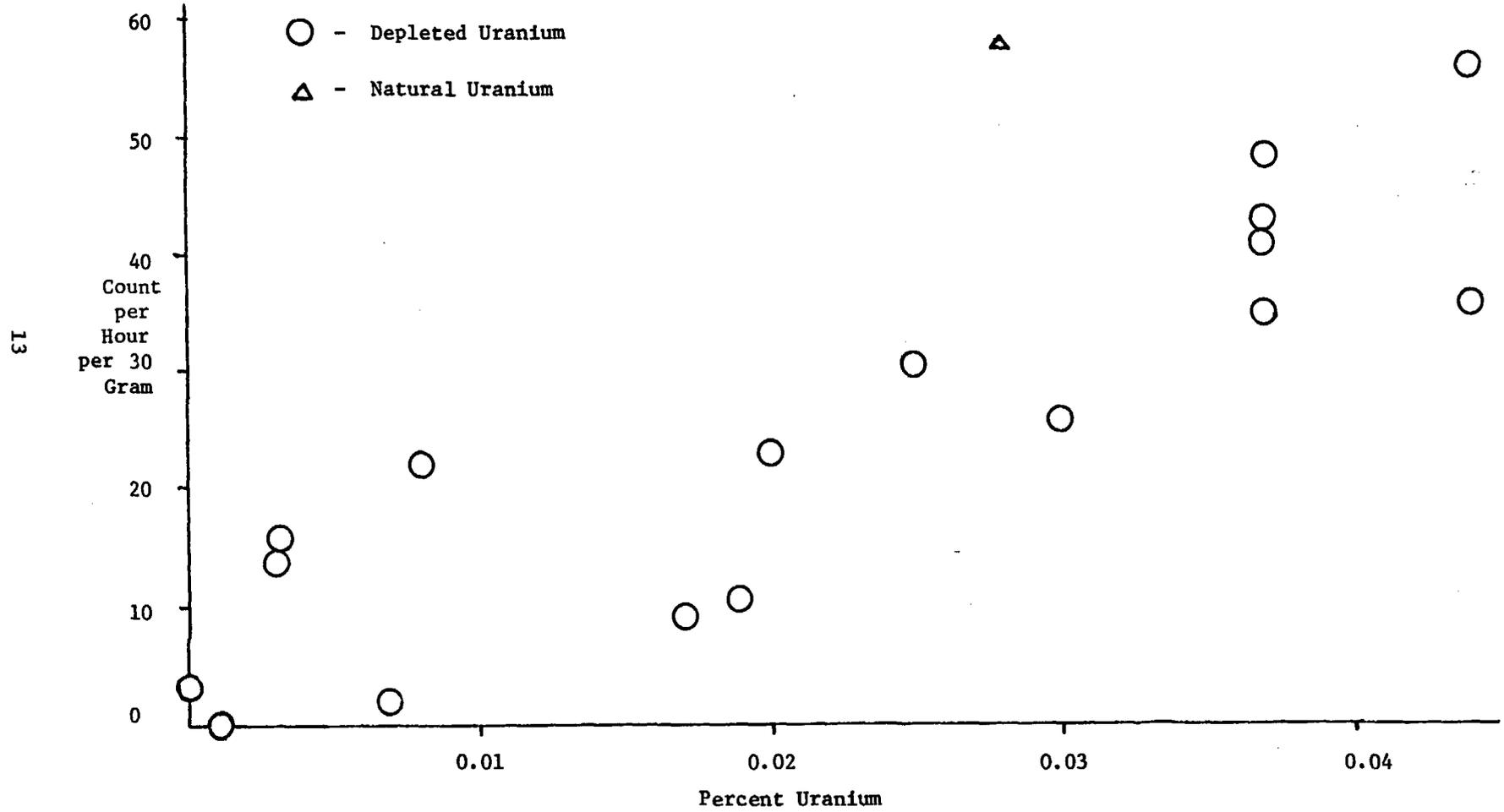
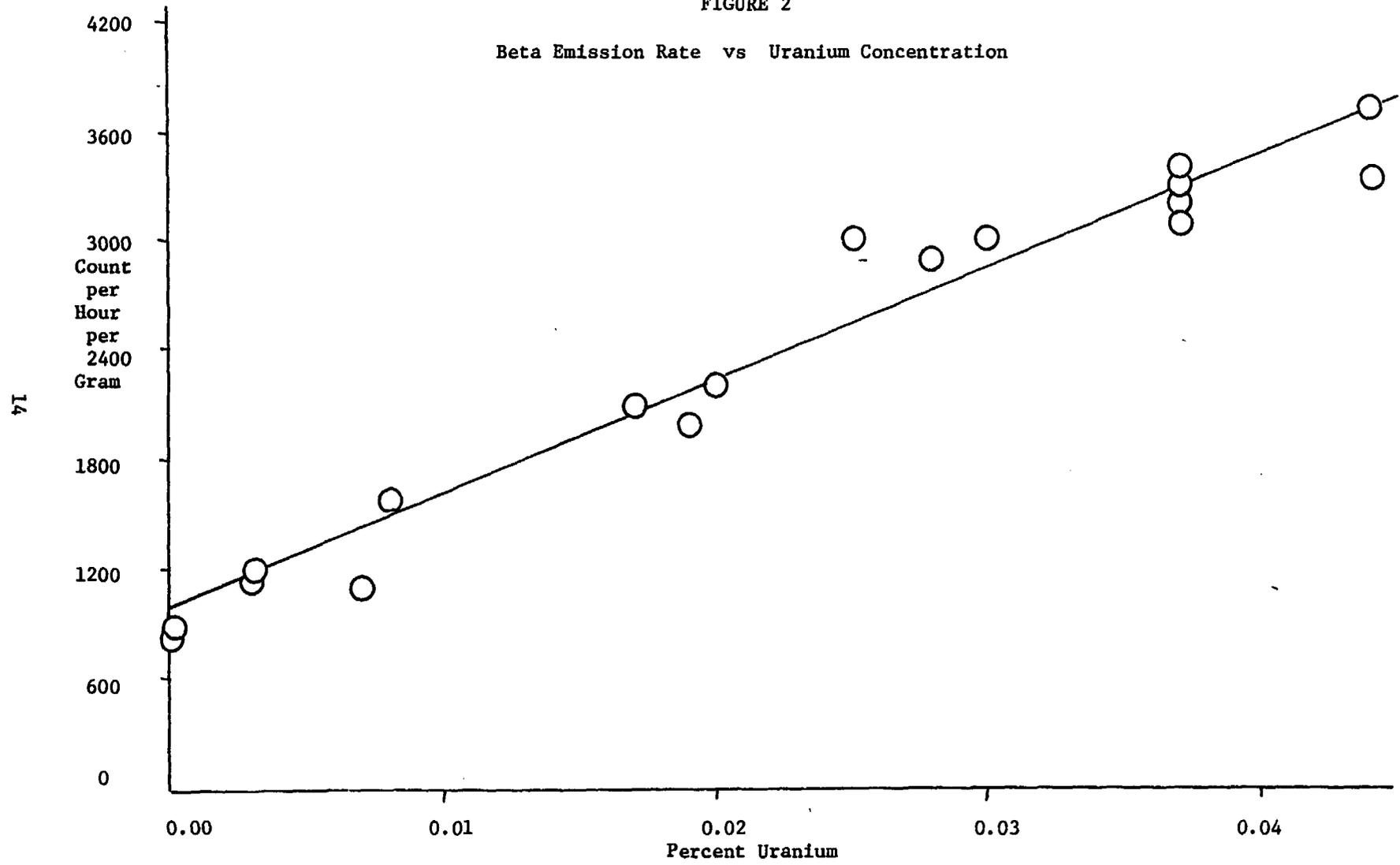


FIGURE 2

Beta Emission Rate vs Uranium Concentration



but not directly proportional. The lowered long-term response may be partially due to filtration of the lower energy beta by the Mylar film and also may be an instance of some fading. The TLD counts and the corresponding dose rate in mrad per year are given in Table 5. The weekly TLD counts are plotted versus the percent of uranium in figure 3. In spite of the low number of TLD counts recorded, the correlations are fairly good and the intercept gives further evidence of beta emission from potassium-40.

#### DOSE RATES FROM ALPHA EMISSIONS

O'Riordan and Hunt (16) calculated the dose rate from uranium porcelain by assuming continuous contact with soft tissue and using Spiers' equation (40) where:

$$D = \frac{nTG}{qP}$$

The dose (D) is proportional to the number of particles emitted per unit volume (n), the mean energy per particle (T), a geometrical function (G), and is inversely proportional to the ratio of the range in porcelain versus soft tissue (q) and the density of soft tissue (p). On an annual basis, for porcelain containing 1000 ppm, they found the dose to be 589 rem. In the present study, the sample having the highest surface emission rate was No. 13 with a flux of 52.1  $\alpha$ /hr/cm<sup>2</sup>. (No. 14 actually demonstrated a flux of 70  $\alpha$ /hr/cm<sup>2</sup>, but contained natural rather than depleted uranium). The effective concentration of uranium in No. 13 was 0.044 percent or 440 ppm. Spiers' equation would indicate an annual dose of 259 rem, which could be misleading, since it assumes a uniform distribution of the element in the matrix.

If instead the manufacturer's specification for the concentration in the enamel portion only is used as a basis for the calculation (.0234 percent) the annual dose drops to a value of 138 rem.

An attempt was made to verify which dose rate was more probable by approximating the history of the alphas being emitted. In depleted uranium, the alpha sources are uranium-238 and uranium-234 with respective energies of 4.2 MeV and 4.8 MeV. The heavier isotope is over 99 percent of the uranium present. The range of the particles was obtained from the tables of Northcliffe and Schilling (41). The transfer of energy for particles was calculated at 2  $\mu$ m increments, assuming the manufacturer's value for concentrations in the body and enamel and also that homogeneity existed only over the maximum range of the particles; i.e., 18 and 24  $\mu$ m in porcelain. The mean energy of the particles reaching the surface and the measured flux were used to calculate the dose in tissue. The result was a total dose rate of 137 rem per year for sample No. 13; consequently, Spier's equation could be applied to the enamel portion alone.

A similar approach was used to calculate the dose delivered beyond 20  $\mu$ m in the soft tissue. The value was an annual dose of 63.7 rem. The absorption in soft tissue was calculated with the aid of Walsh's data (42), which is plotted in figure 4.

The conversion from rads to rems was based on a quality factor of 20 for alphas as recommended by the International Commission on Radiological Protection (11). As was discussed earlier in the report, there is little data available to support the validity of using, at very low dose rates, the

Table 5. Net TLD counts from porcelain teeth

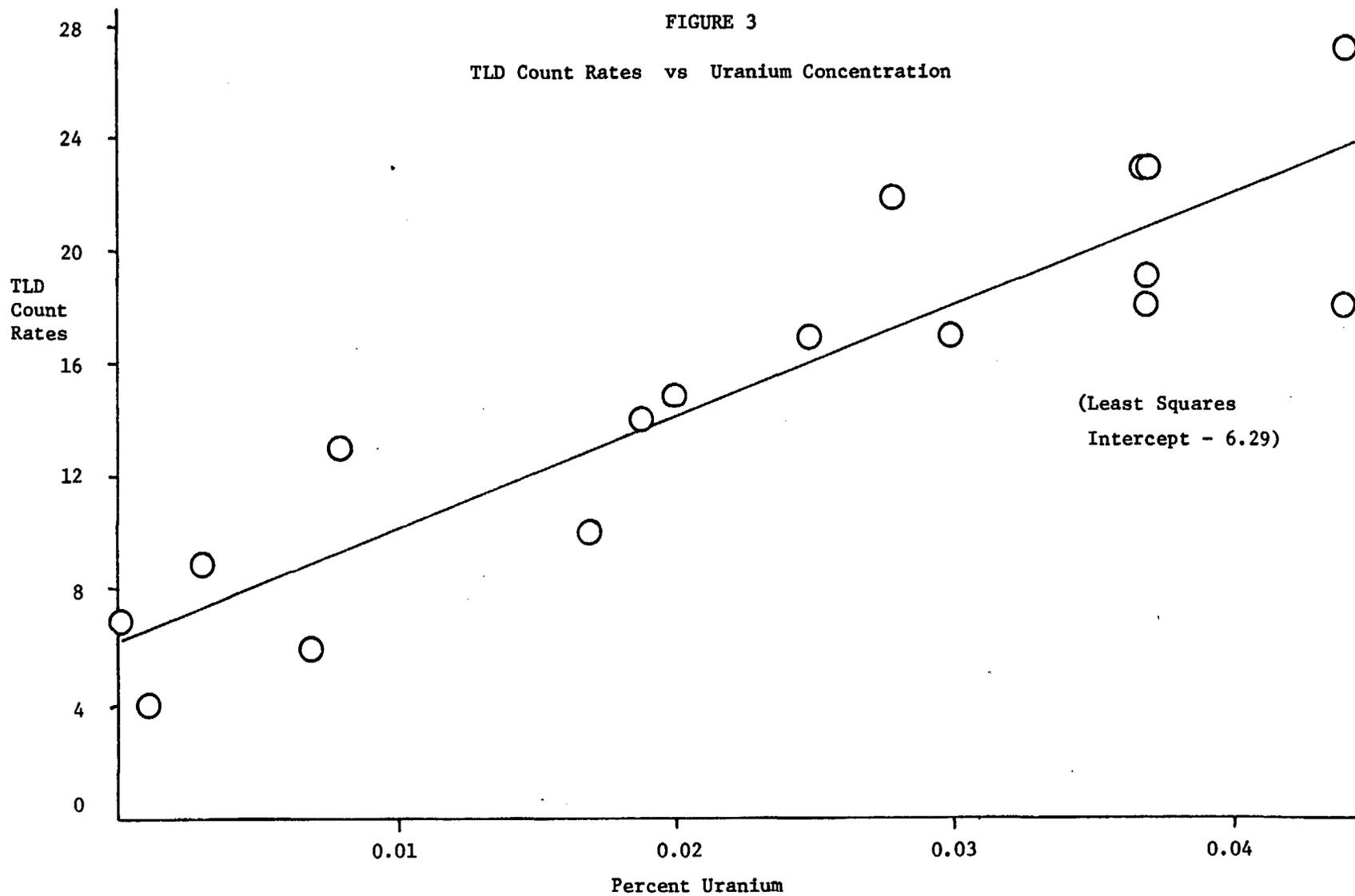
Sample No.	Mrads per year	Eleven-week counts	One-week counts
1	392	120	17
2			23
3			10
4	307	94	14
5			23
6			4
7			27
8			7
9			6
10	468	143	18
11			9
12	350	107	15
13			18
14			22
15	307	94	13
16	363	111	17
17			19
18 <sup>a</sup>			-
19 <sup>b</sup>			9

<sup>a</sup>Not measured

<sup>b</sup>Crown

FIGURE 3

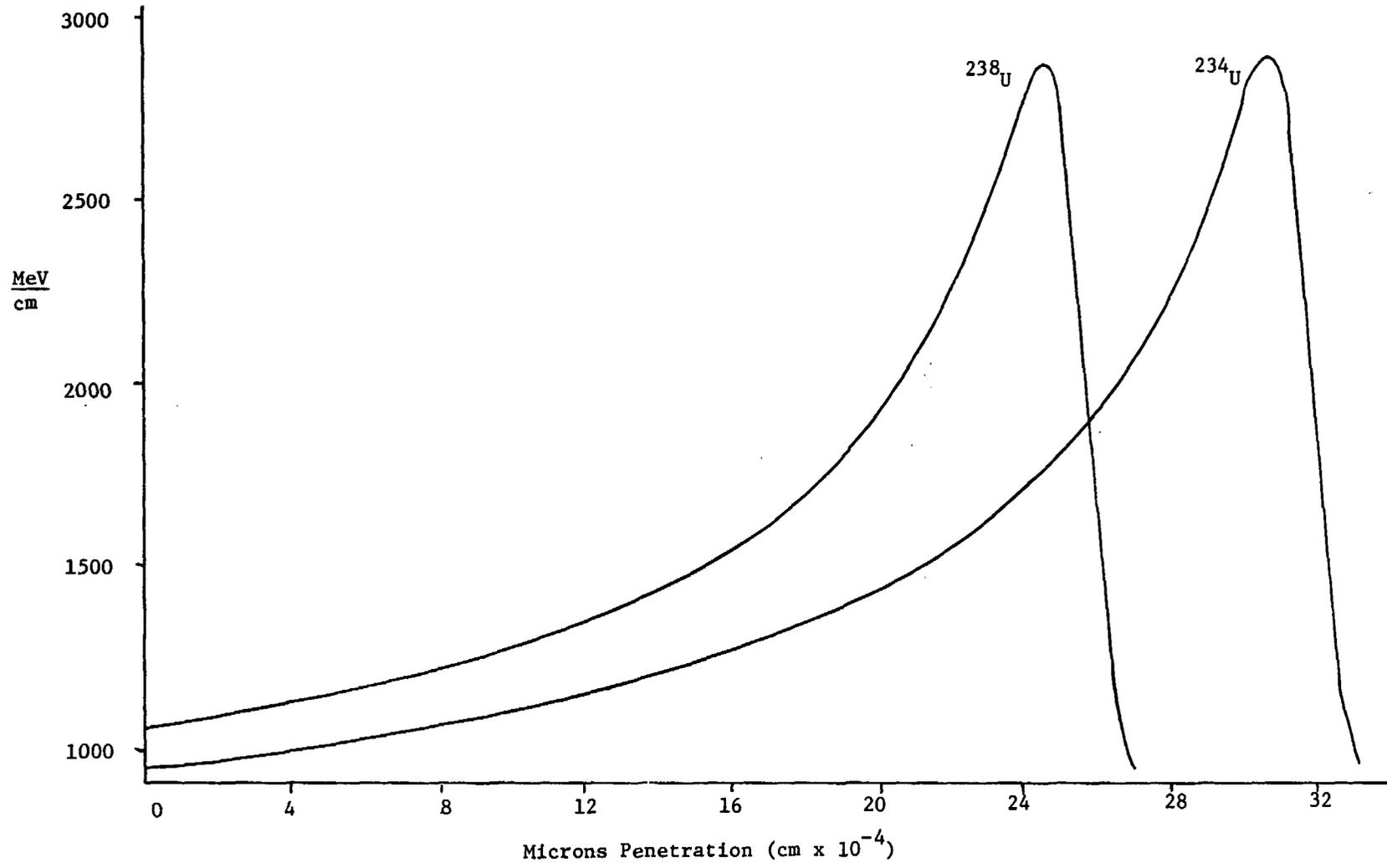
TLD Count Rates vs Uranium Concentration



(Least Squares  
Intercept - 6.29)

FIGURE 4

Alpha Stopping Power vs Penetration in Tissue (Ref. 42)



factors established at much higher dose rates. The tendency for high-LET radiation to increase in effectiveness at lower dose rates implies that the factor of 20 may be an underestimation.

All of the above calculations assume intimate and continuous contact between the teeth and the soft tissue a situation which rarely occurs. Crowns and fixed bridges do remain in position in the oral cavity permanently. Full and partial dentures are commonly removed at night and for cleansing and in some instances are inserted only at meal times. The actions of talking, smoking, chewing, and so forth, vary, to a degree, the volume of tissue which is being exposed. Consequently, for a large fraction of the population involved, it can be expected that the annual dose is from one-third to one-half less than has been calculated for continuous contact.

A further, and possibly more marked reduction in the actual dose depends on the absorption of alpha particles prior to entering the soft tissue. Small air gaps are effective attenuators of alpha particles. A layer of saliva generally coats the teeth and the mucosa and provides additional absorption. A review of the literature does not provide information on the range of thickness of the saliva other than that the total absence of this fluid is rare and usually of short duration. Saliva contains a number of organic components, varies between individuals in density and viscosity, and is potentially a slightly better absorber than an equivalent thickness of water.

Investigation of the thickness of the salivary layer has been initiated at North Carolina State University (43). Preliminary data (nine measurements) indicated a minimum thickness of 120  $\mu\text{m}$  and a range up to 220  $\mu\text{m}$ . Measured alpha attenuation was of the order of 98 percent.

Two other naturally occurring layers serve to reduce alpha penetration. Within a few minutes after brushing, a thin film or pellicle (plaque) forms on natural teeth (44). Initially 1  $\mu\text{m}$  in thickness it can develop to as much as 8  $\mu\text{m}$ . The pellicle may but does not always form on porcelain teeth (45). The pellicle on dentures also has a different composition than that on natural teeth, but both consist of protein substances.

In addition to the plaque, a layer of calculus can form along the margin between the teeth and the gingival tissue. The calculus consists of calcium phosphate, calcium carbonate, and some organic matter.

It is possible that the absorption by saliva, pellicle, air and/or calculus may be sufficient in a portion of the population to prevent any alpha from ever reaching the soft tissue. It is probable that these materials plus food, tobacco, and other residues heavily reduce the absorbed dose in all of the exposed population.

Maximal doses to occupationally exposed persons who handle porcelain teeth may be calculated by considering continuous contact for 40 hours a week. The annual dose to the finger tips for the No. 13 sample would be 30.8 rem. By direct proportion, contact with samples containing in the surface enamel the license exempt quantity of 500 ppm uranium would expose finger tips to 67 rem per year. Although this approaches the maximum recommended limit of 75 rem per year, it also represents a worst-case situation not likely to be encountered. A more realistic value may be obtained by assuming 200 ppm on the average and 20 hours contact per week, which would yield about 13 rem per year to the finger tips.

## DOSE RATES FROM BETA EMISSIONS

In order to calculate the dose due to beta particles it was necessary to establish what fractions of the measured flux were due to uranium and to potassium. Since samples No. 6 and 8 contained minimal amounts of uranium they were used as a basis for determining the ratio of beta to gamma counts for potassium-40. The respective values were 7.65 and 7.63  $\beta$  particles per gamma photon per hours. The factor 7.63 was then used to convert the gamma counts in Table 6 to potassium-40 beta counts with the remainder identified as uranium beta counts. The net beta counts per hour from uranium are plotted versus the uranium content in figure 5. The correlation is higher than in figure 2 and the intercept now occurs at the origin.

The dose due to beta at the surface of a homogeneous planar radioactive source is a function of the thickness of the source. If the thickness exceeds the range of the beta, the surface dose becomes half of the maximum dose in the interior. Porcelain teeth are irregularly shaped nonhomogeneous sources. Thickness on a given tooth may range from 0.2 cm to 0.5 cm for anterior specimens and 0.2 cm to 0.9 cm for molar specimens. The maximum range for uranium beta particles is 0.40 cm and for potassium-40 is 0.24 cm. Mean ranges are about one-third of the maximum. Detailed evaluation would require sectioning of the teeth in multiple planes, determination of the concentration gradient for each radionuclide in each plane and integration over the entire tooth. In lieu of this formidable task it was decided to treat the teeth as infinitely thick planar sources, an assumption which is valid over most of the length of the teeth. Loevinger's equation (47) was employed in which

$$D(P) = 0.8 \times 10^{-8} \bar{E}_{\beta} \tau$$

where,  $D(P)$  = Surface dose on porcelain,

$\bar{E}_{\beta}$  = Mean beta energy, MeV, and

$\tau$  = Disintegrations per gram.

Effective concentrations of uranium and potassium were used to calculate disintegrations per gram.

The dose at an interface between dissimilar materials is modified by scattering of particles. Consequently, Roesch's equation (52) was used to correct for the dose at the surface of the tissue adjacent to the porcelain:

$$D(T) = S_m [2/(1 + (Z_e/Z_a)^{1/2})] D(P)$$

where,  $D(T)$  = Surface dose in tissue,

$S_m$  = ratio of mass stopping power  
for absorber and emitter,

$Z_e$  = atomic number, emitter, and

$Z_a$  = atomic number, absorber.

Values for uranium and potassium contributions and the total absorbed dose rates are given in Table 7. Results would not be significantly different at depths up to 6 mg/cm<sup>2</sup> in tissue.

Table 6. Net beta count rates for Potassium-40 and Uranium in porcelain teeth

Sample	$\gamma$ cts/hr 1.46 MeV( $^{40}\text{K}$ )	$\beta$ cts/hr ( $^{40}\text{K}$ )	$\beta$ cts/hr (U)
1	90	687	1113
2	93	710	1278
3	90	687	594
4	91	694	662
5	102	778	1454
6	81	618	2
7	99	755	1645
8	51	389	0
9	39	298	322
10	88	626	1378
11	63	481	73
12	88	671	799
13	106	809	1561
14	107	816	1193
15	74	565	315
16	70	534	1055
17	127	969	1505
18	72	549	180

FIGURE 5

Uranium Beta Count Rate vs. Uranium Concentration

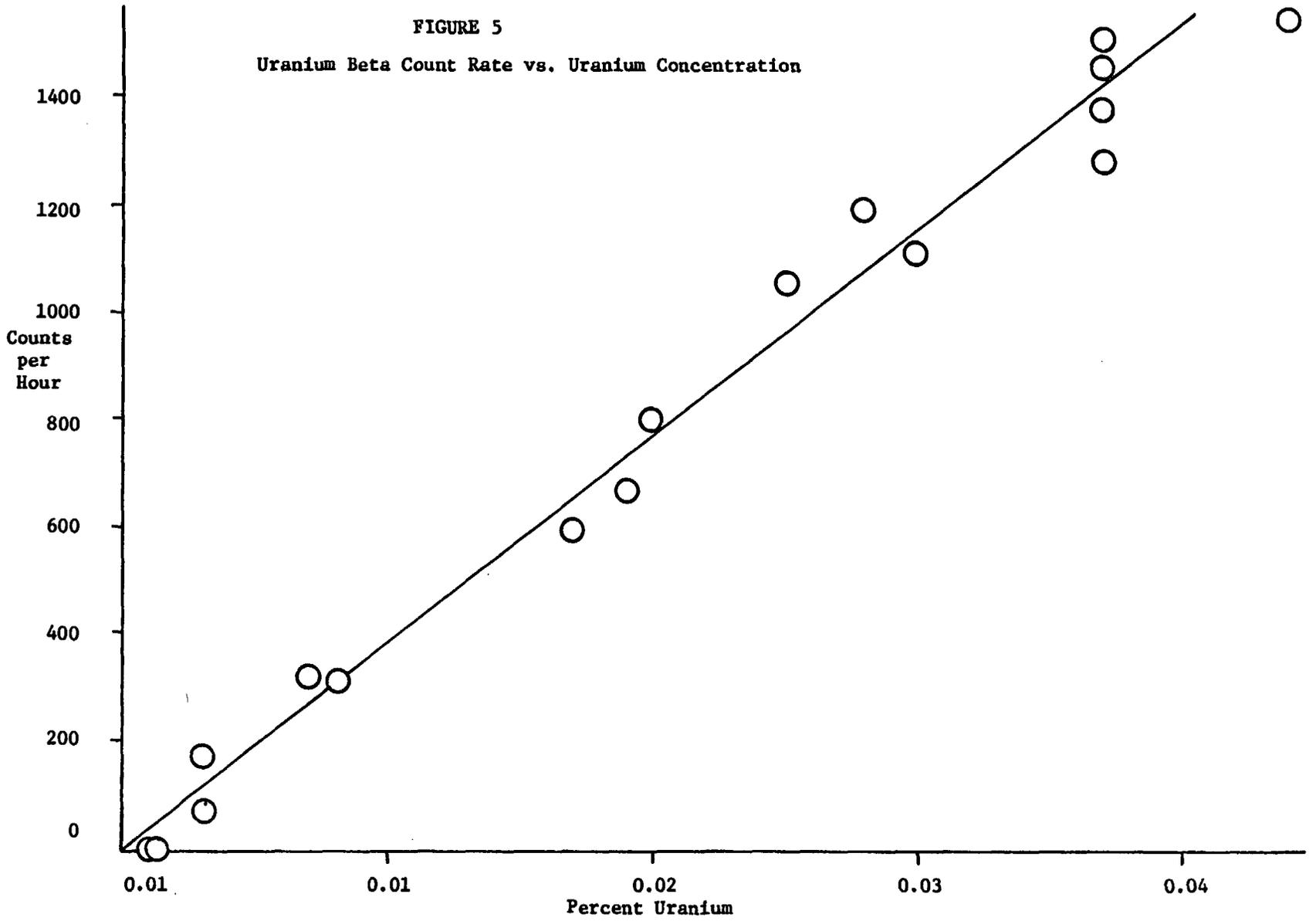


Table 7. Rem per year from beta particle fluxes of porcelain teeth

	$^{238}\text{U}$	$^{40}\text{K}$	TOTAL
1	0.81	0.18	0.99
2	1.00	0.19	1.19
3	0.46	0.18	0.64
4	0.51	0.16	0.67
5	1.00	0.17	1.17
6	0.03	0.13	0.16
7	1.19	0.17	1.36
8	0.00	0.14	0.14
9	0.19	0.08	0.27
10	1.00	0.17	1.17
11	0.08	0.16	0.24
12	0.54	0.16	0.70
13	1.19	0.20	1.39
14	0.76	0.18	0.94
15	0.22	0.16	0.38
16	0.68	0.16	0.84
17	1.00	0.19	1.19
18	0.08	0.14	0.22

As with alpha dose rates, these are overestimations because of the assumption of intimate and continuous contact between teeth and tissues. Particle attenuating factors would not yield as significant a reduction for high energy beta as for alpha.

It is interesting to note in Table 7, that the dose rate from the potassium content of the teeth is equal to or greater than that from uranium in several of the samples.

#### DOSE RATES FROM GAMMA EMISSION

O'Riordan and Hunt reported an annual dose equivalent of 0.004 rem from all photon emission based on a 1000 ppm of uranium in porcelain (16). Assuming that the average concentration is 200 ppm for artificial teeth in the United States the estimated annual dose equivalent becomes less than 1 mrem; inconsequential compared to the particle doses.

In the early stage of the present study some concern was expressed regarding the gamma exposure to employees working in areas where large volumes of teeth were stored. Personnel monitors were placed by the manufacturer in one such area that contained up to one million teeth. The dosimeters were set at positions normally occupied by personnel at intermittent periods during the day. Though the dosimeters remained in the location for a month no reading over background levels were recorded (48). A simple calculation supports these results. Assume one million teeth stacked at an average distance of 2 meters from an employee for 2000 hours per year, and an average concentration of 200 ppm. The specific activity of uranium-238 is  $3.32 \times 10^{-7}$  Ci/g, the specific gamma constant is about 0.04 R per hour for one Curie at a meter. An average tooth weighs about 0.6 grams.

$$(10^6) (2 \times 10^{-4}) (0.6) (3.32 \times 10^{-7}) (2 \times 10^3) (4 \times 10^{-2}) = 0.8 \text{ mR per year.}$$

#### INGESTION AND INHALATION OF PORCELAIN POWDERS

The hazard to occupationally exposed persons from inhalation of porcelain powder containing uranium may be evaluated as follows: The maximum permissible concentration of uranium in air is  $6 \times 10^{-5}$  microcuries per cubic meter (46) and the specific activity is 0.33 mCi per gram which means a concentration of  $1.8 \times 10^{-4}$  grams of uranium per cubic meter. However, the element is present on the average at 200 ppm therefore:

$$1.8 \times 10^{-4} / 2 \times 10^{-4} = 0.9 \text{ gram powder/m}^3.$$

This is at least a magnitude above the acceptable levels of silicates, so the principal hazard would be silicosis, not radiation toxicity (50).

Ingestive hazards may be placed in perspective by referring again to the report of O'Riordan and Hunt (16). They estimated that 300 grams of powder with 1000 ppm uranium could be safely ingested per week. At 200 ppm this would mean 1500 grams per week, the consumption of which would require an unusual appetite.

#### DISCUSSION

It cannot be stated unequivocally that any absorbed dose of radiation is so small as to be completely harmless. Radiation effects have been demonstrated to be cumulative, but are not directly additive. The longer the time period involved in the delivery of the dose the greater the recovery or repair

during the exposure. Data obtained in this study indicate that the doses and dose rates involved, both to the persons wearing dentures and those occupationally exposed, do not appear to present a significant hazard.

Alpha particles may penetrate to the sensitive basal layer in a fraction of the population wearing dental porcelain. Such penetration will be infrequent and of relatively short duration. Research on tissue thickness and salivary coating of the oral mucosa may better define the extent of their exposure.

Beta dose rates to wearers of porcelain teeth are not likely to reach the limit recommended by the International Commission on Radiation Protection for skin, but may approach the limit for other organs. Dose rates from potassium-40 beta particles may be equal to or exceed those from uranium salts.

#### RECOMMENDATION

The conservative approach to radiation protection is to assume that a linear relationship exists between absorbed doses and radiation damage even at very low levels of exposure. Based on this point of view, manufacturers of dental porcelain should be encouraged to develop nonradioactive agents for coloring and fluorescence properties in their products. When practicable substitutes are available, the use of uranium should be discontinued.

The maximum permitted concentration of uranium should be lowered to a level such that the International Commission's limit of 1.5 rem per year cannot be exceeded. The potassium content contributes a smaller fraction of the dose than uranium in most cases, but is less easily controlled by the manufacturer. Estimating a maximum contribution of 0.25 rem per year from potassium-40 and allowing a margin of 0.25 rem per year below the International Commission limit would permit an upper limit of 1.0 rem per year from uranium. The equivalent effective concentration would be 0.037 percent or 370 ppm of uranium. These limits are based on beta exposure of the basal layer.

The American Dental Trades Association has developed a draft standard for uranium content in dental porcelain and porcelain teeth which sets the maximum content at 0.03 percent. This requirement, if promulgated, would be effective for domestic manufacturers and thus apply to about 80 percent of the U.S. market. If the standard were to be accepted by importers as well it would appear to be adequate as the interim guideline until substitutes for uranium can be found.

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