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UNITED STATES ATOMIC ENERGY COMMISSION

MONITORING OF CERTAIN PERSONNEL FOR INTERNAL PLUTONIUM CONTAMINATION

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MONITORING OF CERTAIN PERSONNEL FOR INTERNAL PLUTONIUM CONTAMINATION

By W. H. Langham, A. Murray, III, A. M. Perley, and R. W. Mattison

ABSTRACT

A detailed report is given of the method of determining body internal contamination with plutonium. This method consists of wet-ashing a 24-hour urine sample, extracting the plutonium with cupferron, plating and counting the plate in a proportional alpha counter. Results are presented which were obtained by assaying urine samples from 76 members of the chemistry personnel. These results show that, to date, only the recovery step in processing plutonium has presented a serious health hazard. The results also show a qualitative correlation between the number of high nose counts recorded for an individual and the degree of internal contamination indicated by urine assay. When the individuals were classified into zero- or low-exposure, moderate-exposure and high-exposure groups the difference between the urine counts of those with moderate and high exposure was definitely significant. The difference between the values for the moderate- and low-exposure groups was of doubtful significance.

INTRODUCTION

The unfortunate experience of the radium-dial industry with radium poisoning during the first world war has served to focus attention on the health hazard involved in the processing of large amounts of plutonium.

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Based on observations of a limited number of cases of radium poisoning, a committee called together in 1941 by the National Bureau of Standards tentatively established 0.1 microgram of radium fixed in the body as the tolerance value for humans. Persons exceeding this value are removed from further contact with radium until they again drop below this tolerance value. Obviously it is highly desirable to adopt a similar procedure in the case of persons working with plutonium.

Like radium, plutonium tends to localize in the bone and bombard the sensitive bone cells and bone marrow with alpha radiation. Based on the relative specific activities of plutonium and of radium in equilibrium with its daughter products, plutonium should be only about one-fiftieth as toxic as radium. The tolerance value for plutonium fixed in the human body should then be of the order of 5 micrograms.

Unlike radium, however, plutonium is retained much more completely by the body, 80 percent or more being retained at the end of one year as compared to 10 to 30 percent for radium. Plutonium also has the tendency to deposit in the endostial region of the bone rather than in the shaft as does radium. For this reason the bone marrow and the other more rapidly metabolizing bone elements are more accessible to its alpha particles. These and other observations of differences in the metabolic behavior of radium and plutonium have lead to the tentative adoption of a tolerance value much more conservative than 5 micrograms. Present procedure at this location is to retire anyone showing a persistent excretion of 7 or more counts per minute per 24-hour urine sample from further direct contact with plutonium. This value was derived by assuming (a) that plutonium in amounts of 1 microgram or less can be tolerated indefinitely by the human body without injury of any kind, (b) that the urinary excretion rate in the human is the same as that in the rat, i.e. 0.01 percent per day of the total amount of plutonium present in the body and (c) that the excretion curve in the human levels off sharply within two days after absorption as is the case with the rat.

Present studies indicate that the urinary excretion curve of plutonium by the human does not level off as fast as in the rat and that the daily excretion value is not 0.01 percent but more nearly 0.02–0.03 percent. On this basis 7 counts per minute per 24-hour sample more closely represents 0.5 microgram of body contamination rather than 1 microgram; this provides an additional safety factor. If working conditions can be controlled in such a way that operation can continue under this tolerance value it would be highly desirable.

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This report gives in considerable detail the method of determining body internal contamination with plutonium and the status of the health problems up to July 1945 arising from the processing of this material.

METHOD OF ANALYSIS

The procedure developed for quantitative analysis of urine for plutonium is a rather tedious and time-consuming one, the only justification for which lies in its reasonably high degree of accuracy and consistent results. Several short methods have been suggested and tried elsewhere but are found open to various objections. The ashing of urine and complete solution of the sample destroys any physiologically formed complex which might interfere in the plutonium determination. Complete wet-ashing of four average 24-hour samples requires about 20 working hours for one operator, but much of this time may be devoted to other duties, as continuous attention is not required at all times. The cupferron-chloroform extraction, perchloric acid wet ashing and plating require an additional day. By proper arrangement of work, three experienced operators could turn out up to forty analyses per week. The detailed procedure is presented below.

Method of Collection of 24-hour Urine Specimens

Because of the necessity of detecting such extremely small amounts of plutonium and because of the great possibility of external contamination of the sample, the practice has been to collect urine samples under extremely rigorous conditions.

The subject is directed to stay away from work, and preferably away from the Site, during the 48-hour period preceding the period of collection of the sample to be analyzed. Civilians are permitted to remain in their homes if they choose and the military personnel are requested to spend their time away from the Site. During these 48 hours, new or freshly laundered undergarments are worn and, if possible, freshly laundered outer garments. Certainly, no outer garments previously worn in the Technical Area are used. The hands are washed frequently during this period, preferably with abrasive soap.

The subject reports to the hospital at 8 o'clock in the morning at the close of this "preliminary" period. He remains in the hospital room assigned to him for the following 24 hours. During this period he is-

asked to take little or no fluid between meals and only one cup or glass of fluid at meals. The fluid restriction is imposed in an effort to avoid abnormally large urine volumes.

Upon entering the hospital, the subject empties his bladder, discarding the voiding. After taking a thorough shower and dressing in hospital clothes he is admitted to the collection room. He remains in hospital clothes throughout the entire hospital stay.

A hand counter is available in the room and a note is made as to whether or not the individual has a hand count. The subject is intructed to wash his hands each time before he voids and to wear white cotton gloves during voiding, thus preventing epithelial scales of the hands from falling into the flask and contaminating the sample. All voidings during the next 24 hours are collected in a two-liter Erlenmeyer flask which is placed at such a height that it is not necessary for the person to touch the flask or funnel while urinating. When the collection is completed, the subject dresses and leaves the hospital, leaving his specimen where it was collected. The sample is picked up and delivered to the laboratory by a member of the group carrying out the analyses. Rigid adherence to the procedure described above should permit the collection of a 24-hour urine specimen as nearly free of external contamination as possible.

Ashing of Urine

With the use of sand bath, open coil heater, heat lamp, and electric stirrer the sample is evaporated to near dryness in a 500-ml casserole. If frothing occurs toward the end of the evaporation, a few drops of octyl alcohol are added.

Following evaporation, a total of 100 ml of hot conc. HCl is added, the bottle which contained the sample being rinsed several times with small amounts of the HCl. The material in the casserole is stirred well, several drops of octyl alcohol are added, and then very gradually 50 ml of conc. HNO_3 is added. If all the HNO_3 is added at one time the material will probably bubble over because of the rapid evolution of gas. A Speedy-vap watch glass is used to cover the dish to prevent loss by spattering. As soon as the evolution of gas and the boiling have largely ceased, the material is evaporated on a hot plate. When the volume has become reduced to 30 to 50 ml, 5 to 10 ml of superoxol is added cautiously and the evaporation continued. As the volume gets very small the material usually becomes somewhat frothy and the

fumes become more dense until finally charring begins with the production of a large amount of grey smoke.

When charring is complete, the casserole is removed from the hot plate and before it is entirely cool 50 ml conc. HNO_3 is carefully added, the acid being used to wash down the watch glass. The evaporation is continued on the hot plate. After the evolution of brown fumes has ceased, 5 to 10 ml of superoxol is again added and heating continued. If marked charring occurs a second time the material is treated a third time with nitric acid and superoxol. Evaporation is continued until the material is dry.

The final step in the ashing is accomplished by heating the casserole over a Meeker burner. A Bunsen burner is clamped at a right angle to the Meeker burner to heat the sides of the dish. At this point some further charring occurs and heating is continued until no carbon particles remain.

After cooling, the ash is dissolved as completely as possible in 60 ml 2N HCl. Small amounts are added repeatedly with heating and transferred to a 200-ml centrifuge bottle. Any material which fails to dissolve is washed into the bottle. The material in the bottle is then heated in a water bath or on a hot plate, cooled and centrifuged. The supernatant fluid is poured off into a second centrifuge bottle and the undissolved material is washed twice with about 5 to 10 ml of 2N HCl, the wash being added each time to the second bottle. The undissolved ash is transferred with water to a platinum crucible, the material in the crucible is evaporated to dryness and is then fumed under a drying lamp with about 2 cc of 48 percent HF. When the HF has been removed, the crucible is heated vigorously over a Bunsen burner. The residue is transferred to the centrifuge bottle by dissolving in about 5 ml of 2N HCl. Usually a trace of material remains undissolved.

Extraction and Plating of Ashed Sample

The dilute HCl solution consisting of a total volume of 50 to 75 ml is treated with excess conc. NH_4OH, centrifuged and the supernatant liquid decanted. The precipitate is dissolved in about 25 ml 2N HCl and transferred to a 250-ml separatory funnel, and the centrifuge bottle is washed with two small portions of 0.2N HCl. One mg of Fe is added as $FeCl_3$ in 0.2 ml of 0.2N HCl. The acid is then neutralized* dropwise

* Two to three drops of 0.1 percent aqueous methyl violet indicator may be used, the end point being a bluish-green color which fades upon standing.

with conc. NH_4OH to a point just short of permanent precipitation (if permanent precipitation occurs it is dissolved with dil. HCl) and immediately shaken for about a minute with 1.5 ml of 6 percent aqueous cupferron solution. The complex is extracted into a 40-ml pyrex centrifuge cone with 2-ml portions of $CHCl_3$ until the last portion is colorless.

The $CHCl_3$ is removed by evaporation in a water bath at 65°C. The residue is treated with three-fourths ml conc. HNO_3 and heated 5 to 10 minutes in a water bath followed by addition of three-fourths ml $HClO_4$ (72 percent). The tube is then placed in an oil bath at 130°C which is gradually raised to 180°C over a period of one hour. By the end of this wet-ashing, the solution has been reduced to three-fourths ml of a clear pale-yellow liquid which becomes colorless upon cooling. This solution is then diluted to 4 ml with water and allowed to stand one-half hour with 2 drops of 20 percent NH_2OH-HCl. Forty microliters of $La(NO_3)_3$ solution (200 γLa^{+3}) is added and the tube thoroughly agitated. Lanthanum fluoride is then precipitated by the addition of 1 ml conc. HF. The tube is centrifuged 15 minutes at 2000 RPM, the supernatant liquid decanted and the precipitate washed once with 2 ml 0.1 N HF. The LaF_3 is slurried with distilled water, quantitatively transferred to a platinum foil, evaporated to dryness and flamed. The plate is counted for 30 minutes in a Simpson proportional alpha counter. Blank determinations are run at frequent intervals using samples of urine collected from unexposed persons.

RESULTS

Recovery of Plutonium from Mock Urine Ash Solutions

In order to test the efficiency of the extraction procedure with very low counts, the following synthetic urine ash stock solution was prepared:

NaCl	100.0 gm
K_2SO_4	40.0 gm
$CaCl_2 \cdot 2H_2O$	7.4 gm
$MgCl_2 \cdot 6H_2O$	16.9 gm
$NaH_2PO_4 \cdot H_2O$	24.2 gm
$FeCl_3 \cdot 6H_2O$	240.0 mg
HCl (conc.)	52.0 ml

Dilute to one liter with water.

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To 100-ml portions of this acid solution, equivalent to the wet ash of a single average 24-hour urine specimen, known amounts of plutonium were added. The cupferron extraction was carried out as outlined above with the one exception that no hydroxide precipitation was made. Neutralization was made both with and without the aid of an indicator with comparable recoveries. The plutonium solutions used for "spiking" the mock urine ash solutions were standardized by direct plating on platinum foil using the same pipettes subsequently used in the analysis. Results with 29.3 and 10.0 c/m are presented in Table I.

Recovery of Plutonium from Uncontaminated Urine Samples

A large number of urine samples were collected in the hospital from persons never having been exposed to plutonium. These specimens were divided into two series of samples, each sample consisting of 900 ml. To each sample of one series was added 10.0 c/m of plutonium, to each sample of the other series was added 4.5 c/m. These samples were then carried through the entire assay procedure as presented above. An average blank value of 0.5 c/m (obtained on 24 "unspiked" samples of similarly collected urine) was applied as a correction to all values. The results are given in Table II and show average recoveries of greater than 85 percent.

Effect of Storage and Agitation of Samples Upon Recovery

In order to clarify a point pertinent to another study it was desirable to know whether the recovery of very low counts would be interfered with by agitation and long standing in glassware, through adsorption of plutonium on the container walls. Samples of pooled urine (500 ml) were "spiked" with 10.0 c/m of plutonium, placed in 1-liter soft-glass bottles and stoppered with rubber stoppers. These samples were stored at room temperature for 72 hours. For 38 out of the 72 hours they were shaken moderately by means of a mechanical shaker. The solutions were then analysed in the manner described above. The results are given in Table II, and show that no loss in the number of counts occurred through such handling of samples.

Blank Determinations on Uncontaminated Urines

As a check on the reagents, cleaning of glassware and the method, a total of 24 blank determinations on pooled urine specimens have been

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run, both during the development of the method and throughout the period in which personnel have been monitored. These have averaged 0.48 c/m with a spread of 0.0 to 1.2, only four runs being equal to or greater than 1.0 c/m. The mean deviation from the average was ±0.26 c/m.

Effect of Special Precautions in Sample Collection

Six individuals working with plutonium in highly contaminated areas were asked to submit samples of urine consisting of two over-night voidings. They were asked to bathe and wash their hands thoroughly before collecting each voiding, but were not asked to leave the site during this period. When these samples were analyzed by the above procedure the results obtained were alarmingly high. The great probability that these high values resulted from external contamination led to the adoption of the rather rigorous method of sample collection previously described. The data in Table III give a comparison of results obtained on the same individuals when samples were collected by the two procedures. It is not likely that the fact that the samples collected in living quarters were not true 24-hour samples could account for the 9 : 1 variance in averages.

Data Obtained on Personnel

An attempt has been made to correlate the amount of plutonium found in 24-hour urine specimens with the number of high nose counts recorded for the individual up to the date of analysis, and with the probable degree of exposure and the nature of the job. Daily nose counts are made by taking separate swipes of each nostril and a high nose count is considered to be one in which each nostril yields 50 or more c/m. Probable exposure to plutonium has been arbitrarily classified as (L) zero or low exposure, (M) moderate, and (H) high. This classification was arrived at by consideration of the two exposure factors: degree, based on type of job and quantities of product handled, and time on that job. Three arbitrary classifications of duration of exposure were made by grouping individuals as follows: (1) those on the job up to the average number of months for the 76 individuals minus the mean deviation from the average, (2) those from this point up to the average plus the mean deviation and, (3) those above this latter point. Table IV presents the unselected results obtained in 93 determinations on 76 individuals. These results are summarized

in Table V. All plutonium assays have been corrected (−0.5 c/m) for blank determinations which were made throughout the series.

Although the number of individuals checked in various job groups is, in many cases, too few for sound statistical conclusions, the positive correlation shown in Table V between urine c/m/24 hrs, number of high nose counts and probable exposure is surprisingly good. Only in the cases of those working in dry chemistry and on special problem has the urine count not come up to what might be anticipated from consideration of nose counts and probable exposure. The recovery group personnel has been found to show consistently high urine values which have risen notably with the rapidly increasing quantities of plutonium handled. (Dec. 1944, 50 gm; Jan. 1945, 120 gm; Feb., 50 gm; Mar., 300 gm; May, 1000 gm; June, 3000 gm.) These results show conclusively that the recovery process as now carried out presents a serious health hazard and steps are being taken to improve working conditions. No other stage in the production process seems to present a serious problem to date.

The analyses on 39 individuals having no high nose counts averaged 0.36 c/m while those on 37 individuals, on whom the number of high nose counts averaged 5.7, gave a mean value of 2.0 c/m. The low, moderate and high exposure groups average 0.2, 0.4 and 5.0 c/m respectively. The difference between the low and moderate exposure groups is of doubtful statistical significance. The differences between the low and high and between the moderate and high exposure groups, however, is significant.

Eight individuals with counts over 1.0 c/m were rechecked after intervals of 1 to 2 months. As shown in Table VI, every case of increased nose counts was accompanied by a definite rise in urine counts which in some cases reached very high proportions and which correlate well with the rapidly increasing amount of plutonium handled on the job. The only two sets of specimens collected on consecutive days check well within the expected error. Only one value (O.R.S., 3-17) seems to be unexplainable on any basis other than possible external contamination.

Significant Value

The atistical value of the results presented in this paper can be ascertained, in part, from the following:

(a) The Simpson counter background (102 determinations) was consistently 0.33 ± 0.06 c/m.

(b) The urine blanks (24 determinations) averaged 0.48 ± 0.26 c/m during the time interval over which the data presented in this paper were collected.

(c) Using the theory of propagation of errors, the probable error of a determination for a series of different sample values, counted for a thirty minute period, has been computed by the following formula* which is based upon the three errors: (1) background deviation, (2) blank deviation, and (3) counting deviation.

$$PE = 0.67 \sqrt{\frac{S - 2B}{T} + 2\left(\frac{N}{0.67}\right)^2}$$

Where S = Sample, c/m (corrected for counter background and average blank)

PE = Probable error

B = Mean background, 0.33 c/m

N = Blank mean deviation, 0.26 c/m

T = 30 minutes

The probable errors corresponding to different degrees of probable significance have been calculated by multiplying the probable error by appropriate factors obtained from a Table of Probability of Occurrences of Deviations. The results are presented in Table VII; for example Column four indicates that in 90 percent of all cases the possible error for a sample of 0.9 c/m should be equal to or less than 0.91 c/m. The first values immediately below the heavy line represent the lower threshold of significant values. This statistical interpretation applies only to the specific data included in this report, for it is proving very difficult to maintain the low blank values reported above as the amount of material handled at the site increases. This may be due to the undesirable location of the medical laboratory, or to the sharp increase in the number of samples being analyzed. Computation has shown that the increased counting accuracy resulting from doubling the counting period, would be negligible.

* Acknowledgement is made for the assistance of L. I. Schiff in deriving this expression.

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Table I

Recovery of Known Amounts of Plutonium From Mock Urine Ash Solutions

c/m added	c/m recovered*	% recovery
29.3	28.1	96
29.3	27.3	93
29.3	25.8	88
29.3	29.2	100
Average	27.6	94.2
10.0	9.7	97
10.0	8.5	85
10.0	9.2	92
10.0	10.1	101
10.0	9.1	91
10.0	9.2	92
10.0	9.1	91
10.0	8.8	88
10.0	9.6	96
10.0	10.1	101
10.0	9.2	92
Average	9.3	93.3
Mean deviation from average		±3.7

* An average blank value of 0.5 c/m was subtracted from each result.

Table II

Recovery of Known Amounts of Plutonium From 900 ml Samples of Urine

c/m added	c/m recovered†	% recovered
4.5	3.6	81
4.5	4.8	105
4.5	4.4	99
Average	4.3	95
10	10.4	104
10	9.3	93
10	8.3	83
10	8.9	89
10	8.1	81
10	9.6	96
10	9.4	94
10	7.3	73
10*	8.8	88
10*	9.4	94
10*	9.6	96
10*	7.4	74
Average	8.9	89
Mean deviation from average		7.5

*500 ml samples of urine stored at room temperature for 72 hours and mechanically shaken for 38 hours in soft glass containers.

† An average blank value of 0.5 c/m was subtracted from each result.

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Table III

Effect of Method of Collecting Samples on Counts Found in Urine

c/m and Place of Urine Collection	
In Quarters*	In Hospital
10.1	2.2
41.6	4.3
16.1	3.4
2.8	0.1
17.8	
30.6	1.1
19.8	2.2

*Samples were two overnight voidings with one working day in between.

Table IV

Individual Results of Urine Assays of Chemistry Personnel Classified on Basis of Nose Counts, Probable Exposure and Job

Sample	c/m/24-hr Sample	Number High Nose Cts.	Prob. Exposure	Job Nature	Job CM Group
41	1.1	18	H	Recovery	5
159	2.5	21	H	Recovery	5
209	7.0	27	H	Recovery	5
66*	4.3	24	H	Recovery	5
147	4.8	27	H	Recovery	5
194*	11.4	29	H	Recovery	5
213*	21.4	31	H	Recovery	5
77†	3.4	7	H	Recovery	5
193*	4.2	11	H	Recovery	5
162	3.2	5	H	Recovery	5
208	4.7	11	H	Recovery	5
85	0.2	0	M	Met. Remelt	8
210	1.7	1	M	Met. Remelt	8
70	0.0	1	M	Anal.	9
199	1.3	1	M	Anal.	9
45	2.8	3	M	Anal.	9
141	0.3	3	M	Anal.	9
142	0.3	3	M	Anal.	9
50	1.3	10	H	Met. Rolling	8
96	1.4	10	H	Met. Rolling	8
55†	2.2	10	H	Recovery	5
161	2.7	11	H	Recovery	5
47	0.1	3	M	Dry Chem.	5
61	0.3	4	M	Anal.	6.9
65	0.6	1	M	Metal Prop. and Fabric.	8 5
67	0.2	1	M	Purif.	
74	0.1	2	M	Metal Process. and Fabric.	8
79	0.3	3	M	Met. Prod.	8
81	0.5	1	M	Anal.	9
100	1.0	4	M	Anal.	9

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Table IV (Cont'd.)

Sample	c/m/24-hr Sample	Number High Nose Cts.	Prob. Exposure	Job Nature	GM Group
102*	0.4	16	M	Dry Chem.	5, 15
104	0.3	15	M	Metal Prod. and Fabric.	8
106	0.1	2	M	Sp. Prob.	6
113	0.1	1	L	Recovery	5
114	0.4	1	M	Wet Chem.	11
115	0.2	1	M	Purif.	5
116	0.1	2	M	Sp. Prob.	6
134	0.5	6	M	Metal Prod. and Fabric.	8
135	0.1	3	M	Anal.	9
136	0.5	1	M	Decont.	12
137	0.0	1	M	Sp. Prob.	6
138	0.0	2	M	Anal.	9
139	0.4	3	M	Metal Prod. and Fabric.	8
144	0.3	1	M	Anal.	9
160	0.3	1	L	Anal.	9
163	3.7	3	H	Metal Prod.	8
187	2.3	7	M	Recovery	5
195	0.8	2	M	Purif.	5
198	0.9	1	M	Anal.	9
200	0.8	4	M	Purif.	5
206*	1.7	1	M	Decont.	12
42	0.0	0	L	Metal Fab.	8
43	0.6	0	M	Purif.	5
46	0.1	0	L	Quantity Control	1
49	0.3	0	L	Mach. Shop	1
51	0.3	0	L	Mach. Shop	11
53	0.5	0	M	Purif.	5
54	0.1	0	L	Recovery (drafting)	5

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Table IV (Cont'd.)

nple	c/m/24-hr Sample	Number High Nose Cts.	Prob. Exposure	Job Nature	CM Group
57	0.0	0	L	Dry Chem.	5
58	0.0	0	M	Anal.	9
59	0.0	0	L	Drafting	1
62	0.0	0	L	Tech. Pool	1
63	0.0	0	L	Metallurgy	11
69	0.2	0	L	Quantity Control	1
71	0.0	0	M	Dry Chem.	5
73	0.4	0	L	Quantity Control	1
75	0.0	0	L	Metal Fab.	8
78	0.4	0	M	Purif.	5
80	0.1	0	L	Procurement	1
82	0.0	0	L	Dry Chem.	5
84	0.4	0	L	Mach. Shop	1
86	0.2	0	L	Metallurgy	11
101	0.1	0	M	Metal Processing	13
103	0.5	0	L	Recovery	13
105	0.3	0	L	Electroplating	4
107	0.1	0	M	Decont.	12
108	0.1	0	M	Purif.	5
110	0.1	0	M	Purif.	5
111	0.2	0	M	Purif.	5
112	0.2	0	M	Dry Chem.	5
132	0.2	0	M	Metal Process. and Fabric.	8
133	1.5	0	M	Purif.	5
140	0.0	0	L	Purif.	5
143	0.2	0	L	Purif.	5
179	0.7	0	M	Purif.	5
196	1.3	0	M	Anal.	9
201	1.4	0	M	Anal.	9

Table IV (Cont'd.)

Sample	c/m/24-hr Sample	Number High Nose Cts.	Prob. Exposure	Job Nature	CM Group
202	1.0	0	M	Anal.	9
203	1.5	0	M	Anal.	9
204	1.2	0	L	Anal.	9
205	1.6	0	M	Decont.	12
140	0.0	0	L	Purif.	5

* Slight hand count.
† Contaminated cut.

Table V

Effect of Degree of Exposure on the Counts of Plutonium Found in Urine

Group	Job	Group Ave. c/m/24-hr urine sample	Spread c/m	No. of indiv. w. high nose ct.	No. of Individuals and probable exposure L*	M*	H*
CM-1	No Exposure	0.2	0.0—0.4	0	8	0	0
CM-4	Electroplating	0.3	0	0	1	0	0
CM-5	Recovery	4.7	0.1—21.4	7	2	1	5
	Purification	0.5	0.0—1.5	4	2	12	0
	Dry Chemistry	0.1	0.0—0.4	2	2	4	0
CM 6	Sp. Problems	0.1	0.0—0.3	4	0	4	0
CM-8	Metal Prod. and Fabric.	0.6	0.0—3.7	8	2	8	2
CM-9	Analytical	0.7	0.0—2.8	9	2	12	0
CM-11	Metallurgy	0.2	0.0—0.4	1	3	1	0
CM-12	Decontamination	1.0	0.1—1.7	2	0	4	0
CM-13	Processing	0.3	0.1—0.5	0	1	1	0
Low Exposure		0.2	0.0—1.2	2		23	
Moderate Exposure		0.4	0.0—2.8	29		46	
High Exposure		5.0	1.1—21.4	7		7	
No High Nose Cts.		0.4	0.0—1.5	0		39	
High Nose Counts		2.0	0.0—21.4	37		37	

* L, M and H mean low, moderate and high exposure, respectively.

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Table VI

Recheck of Individuals Over 1.0 c/m

Sample	Date	c/m/24-hr Urine	No. of High Nose Cts.
66	3-22	4.3	24
147	5-4	4.8	27
194	6-7	11.4	29
213	6-17	21.4	31
41	3-16	1.1	18
159	5-6	2.5	21
209	6-14	7.0	27
162	5-13	3.2	5
208	6-14	4.7	11
77	3-25	3.4	7
193	6-7	4.2	11
55	3-19	2.2	10
161	5-10	2.7	11
45	3-17	2.8	3
141	5-1	0.3	3
142	5-2	0.3	3
50	3-18	1.3	10
96	4-9	1.4	10
196	6-3	1.3	0
201	6-4	1.4	0
202	6-12	1.0	0

Table VII

Theoretical Error of a Determination

Sample c/m	Probable Error (±c/m) With Probability of Significance for 30-minute Counting Period				
	50%	75%	90%	95%	99%
0.3	0.36	0.62	0.88	1.05	1.38
0.4	0.36	0.62	0.88	1.05	1.38
0.5	0.37	0.63	0.89	1.06	1.40
0.6	0.37	0.63	0.90	1.07	1.40
0.7	0.37	0.63	0.90	1.08	1.41
0.8	0.37	0.64	0.91	1.08	1.42
0.9	0.37	0.64	0.91	1.09	1.43
1.0	0.38	0.64	0.92	1.09	1.43
1.2	0.38	0.65	0.92	1.10	1.45
1.4	0.38	0.66	0.94	1.11	1.46
1.6	0.39	0.66	0.95	1.13	1.48
1.8	0.39	0.67	0.95	1.14	1.49
2.0	0.39	0.67	0.96	1.15	1.51
3.0	0.41	0.71	1.00	1.20	1.57
4.0	0.43	0.74	1.05	1.25	1.64
5.0	0.45	0.77	1.09	1.30	1.71
7.0	0.48	0.82	1.16	1.40	1.83
10.0	0.52	0.90	1.28	1.53	2.00

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