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Clearance of Radioactive Dust from the Human Lung

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One of the important potential health hazards associated with the atomic energy industry is that of air-borne radioactive dust. This is not a new problem, since radium and uranium mines have always had radioactive dust and radon gas. Indeed, the only practical experience with this hazard originated in the European uranium mines, where there was an extremely high incidence of lung cancer.[1]

The control of radioactive dust is in one sense an economic matter, because the greater the expenditure for ventilation equipment the less the degree of personnel exposure. The problem then has been to establish reasonable levels of exposure which would insure safety of the workers without being overly conservative and therefore too expensive. Two approaches to this problem have been made. The known average concentration of radon (3×10^{-9} curies/liter) in the Schneeberg and Joachimstal mines has been used as the basis for a recommended maximum permissible concentration of 10^{-11} curies/liter.[2] In practice, however, 10^{-10} curies/liter has been used to a considerable extent. The other approach to the problem of establishing safe working concentrations is based on a maximum permissible radiation dosage rate to the lung of 300 millirem/week.[3] An estimate is made of the air concentration of the particular dust in question which if inhaled over the period of a working week would deliver this radiation dosage to the lung. It is pertinent to note that the value of 300 millirem/week is also used for whole-body exposure to penetrating radiation and is derived from estimates of the dose which would not be damaging to the blood-forming organs.[4] Whether it is reasonable to utilize the same permissible dosage for both the lung and the blood is not answerable at the present time.

It is of interest to compare the dose rate of 300 millirem/week with that calculated for the maximum permissible exposure to radon. Harley[5] has calculated that exposure to 10^{-10} curies/liter, assuming 50% retention of the radon daughter products on the bronchial epithelium, would deliver 50 rem/week. This is 150 times higher than the 300 millirem/week permissible value. This calculation must be tempered by the lack of information on the actual fraction of inhaled radon daughter products deposited on the bronchial mucosa and the question of whether the radon or thoron daughters, in fact, remain in the lung or become rapidly dissipated in the blood stream. This latter point, that of the effective half-life of the daughters of radioactive gases, forms the subject of some experiments to be reported here.

Although the dosages from the current maximum permissible concentration of radon and the maximum permissible exposure rate to the lung of 300 millirem/week do not compare very closely, it is well to point out that the use of the more conservative value involves a number of assumptions which are, at best, crude approximations. For example, one must assume that a certain fraction of the inhaled dust is retained and that this retained dust has a biological half-life of a certain magnitude. These factors, together

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with the radiological half-life and the effective energy of the emitted radiation, enable one to calculate the permissible air-borne concentrations. There may be a major fallacy in this approach, since most of the lung cancers observed in the European uranium mines, and these presumably were due to radiation, occurred in the epithelium of major bronchi. The walls of such bronchi are sufficiently thick to prevent the penetration of the alpha and beta radiations (which are the important ones so far as lung damage is concerned) from the outside of the bronchial wall through to the inner lining, which is the target organ in question. Consequently, radiation to the bronchial mucosa must originate largely from the particles which are initially deposited in the bronchi or which are swept out over them by the ciliary mechanism. From this point of view, the radioactive particles which are rapidly removed from the lung constitute the real hazard. The estimates for the maximum permissible air concentration are, however, based on the fraction which remains behind in the lung, and, for all we know, this material deposited in the alveoli may be rendered harmless by the comparative radioresistance of the alveolar structures. This, in one sense, would be analogous to the situation in which lead is detoxified by being deposited in the skeleton and its damaging effects occur while in transit to and from the bone. If this, in fact, is the truer picture of the situation, the better estimate of the hazard would involve information on the fraction of inhaled radioactive particles which are deposited on the bronchial mucosa and the rate at which they are removed. It is this point, namely, the speed with which radioactive particles are removed by ciliary action, that constitutes the subject of the second group of experiments to be reported here.

EFFECTIVE BIOLOGICAL HALF-LIFE OF THORON DAUGHTERS

As indicated in Figure 1, the daughters of thoron gas are more suitable than those of radon for the estimation of the effective half-life in the lung, because they have a radiological half-life of about 10½ hours, compared with 30 minutes for radon daughters. In addition, ThC and ThC′ have gamma radiations of greater than 1,000,000 electron volts, which make their detection from the outside surface of the chest feasible.

In these studies, thoron gas was dispersed into a 1000 cu. ft. chamber by bubbling air vigorously through a 2 mc. solution of ThX. At the same time a cloud of kaolin (aluminum silicate, $H_4Al_2Si_2O_9$, density 2.1) dust was maintained in the same chamber. After the thoron supply to the room is shut off,

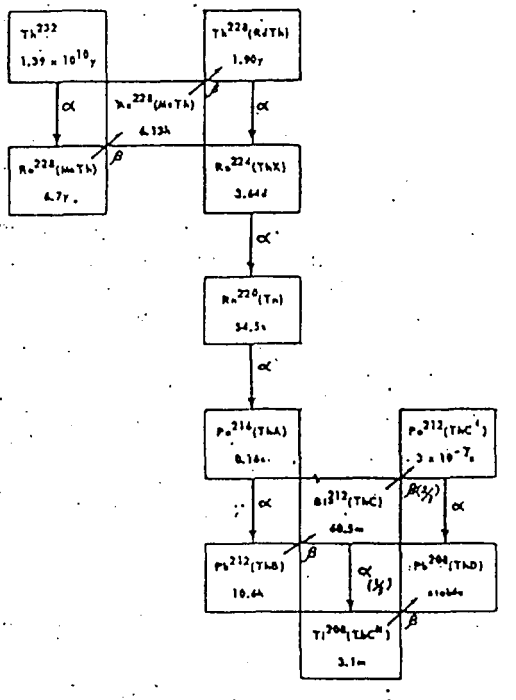

Fig. 1.—Thorium decay series.

ThA, with a half-life of 0.16 second, decays almost immediately and the remaining activity is governed by ThB, with a half-life of 10.6 hours. The thoron daughters are produced in atomic form or in very small aggregates, and they adsorb onto the surfaces of suspended dust and are deposited in the lung with the carrier dust. Since they are attached to the dust in a tenuous fashion, we were interested in determining whether the daughters were quickly washed off and carried away from the lung by the blood.

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A concentration of 10^{-9} curies/liter of ThB was maintained throughout the experiments, of which six were performed on four healthy subjects. The dust was inhaled for approximately one hour through a face mask attached by a short length of rubber hosing to a port in the dust chamber. Cascade-impactor samples were taken during the early and latter parts of the breathing period. When the subject completed the dust inhalation, he washed his face and removed any dust from the pharynx and mouth by gargling. He then seated himself before a scintillation counter which utilized a cylindrical sodium iodide crystal, 2 in. in diameter and 1½ in. thick. This crystal was mounted in a lead shield in such a manner that the front of the crystal could be pressed against the subject's chest. During all experiments the crystal was positioned on the anterior surface of the thorax on the midline at the level of the second rib. The crystal received the gamma radiations emitted by ThC and ThC″. The particle-size distribution of the kaolin dust was quite uniform and ranged in all the experiments from 1.1μ to 1.3μ mass-median diameter.

The results of these studies are presented in Figure 2, where the experiments were divided into two groups on the basis of the initial count rate recorded from the surface of the chest. It can be seen that the effective half-life, as determined from both curves, was about nine hours. This value is very close to the radiological half-life of 10.6 hours, indicating that the biological half-life is in the order of 60 hours. This study indicates that, once deposited, the thoron daughter products, and by analogy radon daughter products (because their chemical forms are almost identical), are removed slowly enough so that the effective half-life is not significantly different from the rate of radiological decay.

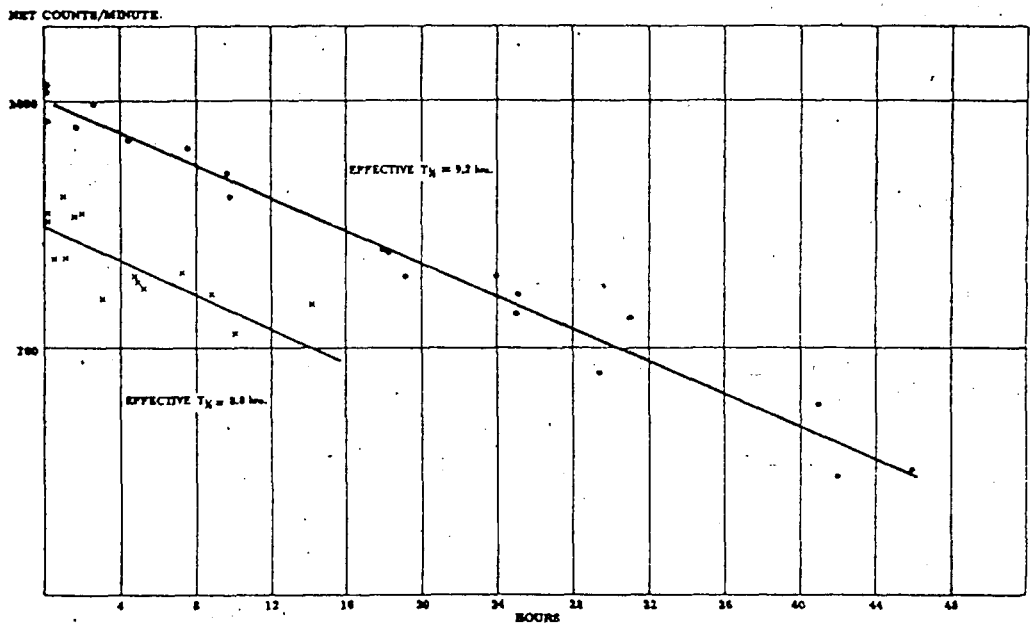

Fig. 2.—Net gamma count rate from the surface of the chest following inhalation of thoron daughters.

CLEARANCE RATE OF DUST BY THE CILIARY MECHANISM

As indicated previously, the hazard of inhaled radioactive insoluble dust may come from those particles which are removed by ciliary action rather than from the ones remaining behind, and it was of interest to determine the rate of this removal in humans. Animal studies have indicated that the linear

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velocity of particles carried on the bronchial mucosa is quite high, about 1 to 3 cm. per minute, depending on the portion of the respiratory tract.[6] In addition, it is common experience of radiologists that iodized oil (Lipiodol) used for bronchography is frequently removed within one day. Animal studies utilizing radioactive dusts also indicate that the bronchial mucosa is cleared in a matter of hours.[7]

For these studies, metallic iron powder was used, which had been irradiated with neutrons in an atomic pile to produce a radioactivity level of 100μc of Fe^{59} per gram of iron. This iron isotope has a strong gamma component and consequently is also suitable for detection from the surface of the chest. The radioactive iron powder was placed in a Waring Blendor which was fitted with a tight cover. The cover had an opening for a short breathing pipe and a port for the inlet of a cascade impactor. At the beginning of the experiment, the subject placed his mouth around the breathing pipe. The Blendor was turned on for three seconds, and at the end of this interval the subject was instructed to take a breath; at the same time a cascade-impactor sample was obtained. The Blendor was turned off, and the subject rinsed his mouth and pharynx by gargling with water and then went quickly to the scintillation counter, as described before.

In the experiments to be reported here, eight studies were performed, four with particle sizes of 3.4μ-4.3μ and four with particle sizes of 1.4μ-2.3μ mass-median diameter.

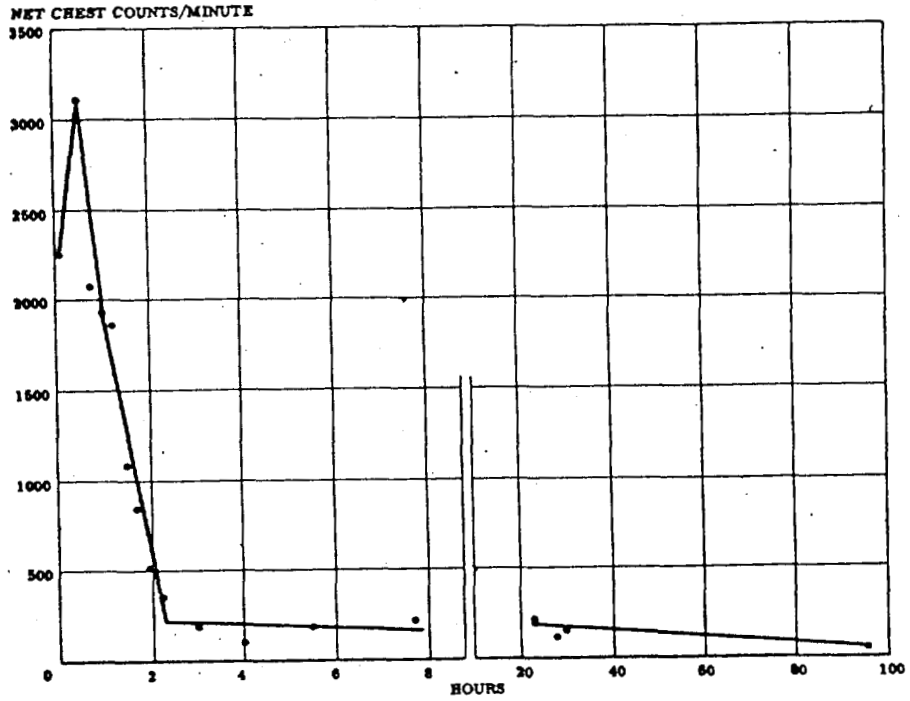


Fig. 3.—Net gamma count rate from the surface of the chest following inhalation of radioactive iron dust in Subject A. B.

Three of the four studies with the larger particle sizes were remarkably similar. Figure 3 illustrates an experiment in which the count rate from the surface of the chest started at about 2000 counts per minute, rose rapidly several hundred counts more, and fell precipitously to about 5% of the initial activity in two hours. Figure 4 presents a similar response in another subject. During the course of this run, it occurred to us that the activity which was lost from the chest

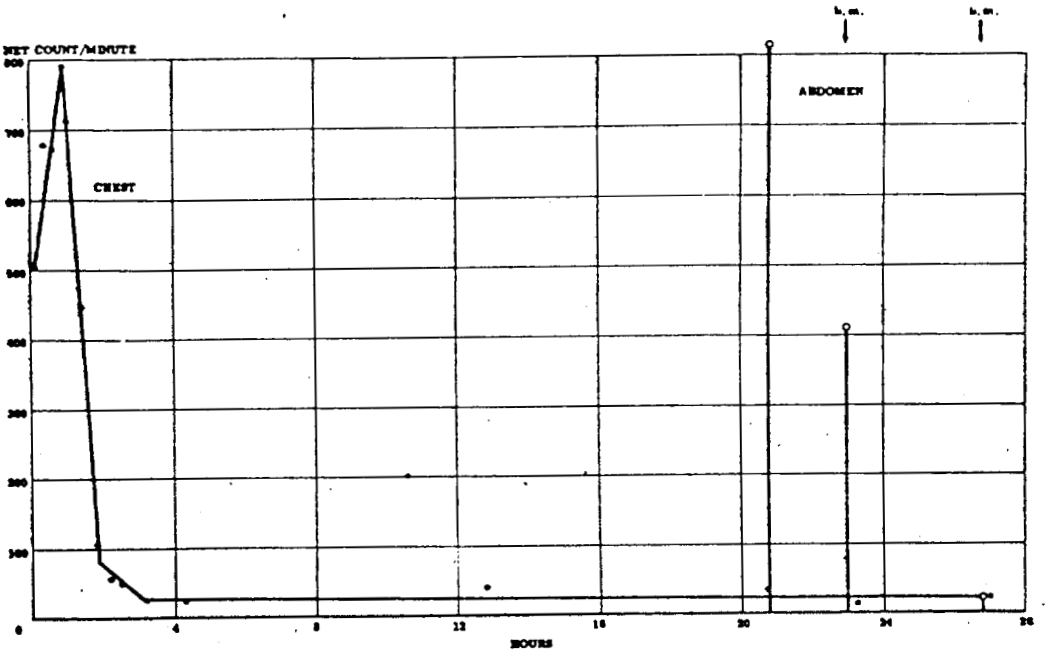


Fig. 4.—Net gamma count rate from the surface of the chest following inhalation of radioactive iron dust in Subject R. A.

should appear in the abdomen, because particles raised by ciliary activity are swallowed. When the subject placed his abdomen against the crystal at about the level of the umbilicus, the indicated high count rate was observed. A saline cathartic was administered, after two defecations the count fell to very low levels. Blood samples taken during the period of rapid clearance from the chest indicated no detectable radioactivity.

The next subject (Fig. 5) was unusual. Whereas the other subjects achieved a high chest count with one respiration, this subject had to inhale about four times in order to reach a counting rate of only 300 per minute. In retrospect, the subject recalled that while breathing he had kept his tongue close to the hard palate. It is possible that because of the narrowing of the breathing passage through the mouth, the velocity of the air

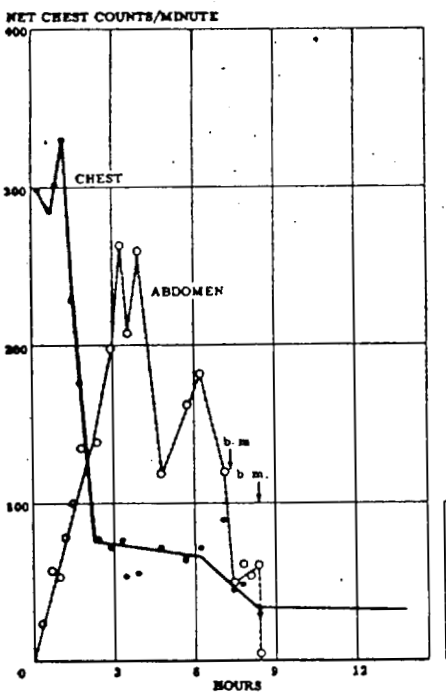
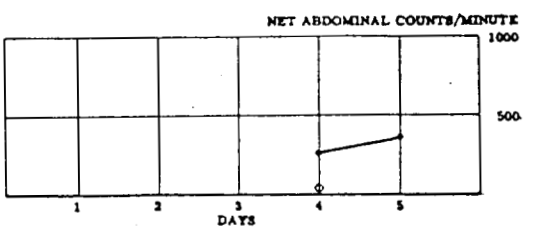


Fig. 5.—Net gamma count rate from the surface of the chest following inhalation of radioactive iron dust in Subject L. A.



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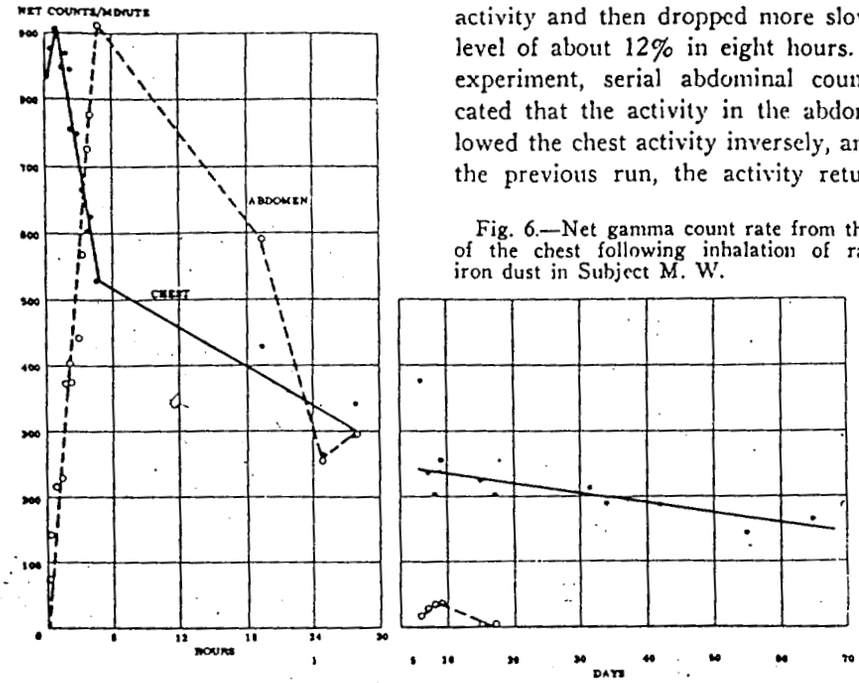

Fig. 6.—Net gamma count rate from the surface of the chest following inhalation of radioactive iron dust in Subject M. W.

became high enough to impact more particles in the pharynx so that fewer reached the lung, and of those that did there was a greater predominance of smaller particles. In any event, this subject again showed the initial rapid drop in count rate, but this time the fall stopped at about 25% of the initial activity and then dropped more slowly to a level of about 12% in eight hours. In this experiment, serial abdominal counts indicated that the activity in the abdomen followed the chest activity inversely, and, as in the previous run, the activity returned to background levels only after several bowel evacuations.

The response to the smaller particles is illustrated by Figure 6. Here we see that there is again a rapid initial fall, in this case in 4 hours to about 60% of the initial activity, and then a slower fall over the course of 30 hours to a level which is thereafter sustained for the remainder of the observation period of 70 days. It is worth noting (Fig. 7) that in two subjects receiving the smaller particles the secondary 30-hour clearance period appeared to consist of two parts, with

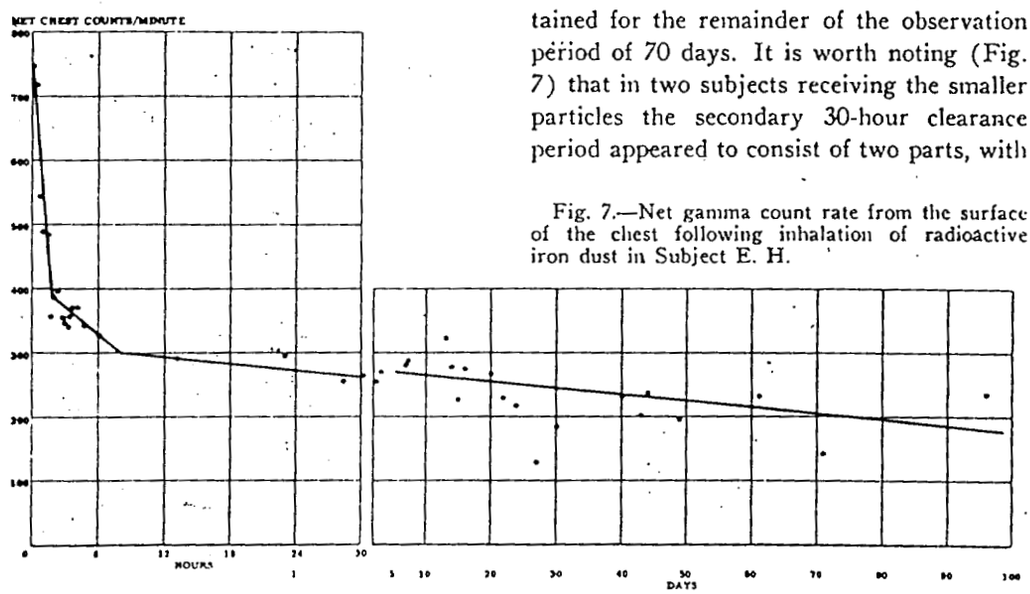

Fig. 7.—Net gamma count rate from the surface of the chest following inhalation of radioactive iron dust in Subject E. H.

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a more rapid initial phase which resembled the secondary clearance in subjects receiving the larger particles (Figs. 4 and 5).

In summarizing the data in Figure 8, the average time for completion of the first decay curve in the four experiments with the larger particle sizes, was 2.1 hours, with a range of 1.9 to 2.3 hours, and the average percentage of the material cleared from the lung after this period was 87%, with a range of 75% to 95%. In two of these subjects, there was a second clearance period, lasting 3.2 and 6.5 hours, which reduced the retention about another 10%.

In the four experiments where the subjects inhaled the smaller particle sizes, the average time for completion of the first clearance period was 2.4 hours, with a range of 1.6 to 4.0 hours, and the average activity cleared from the chest after this period was 47%, with a range of 36% to 53%. All these subjects exhibited a second, shallower clearance slope which ended in an average of 33 hours, with a range of 31 to 36 hours. This second clearance period increased the lung clearance from an average of 47% to 68%.

COMMENT

The technique of measuring the clearance of radioactive particles from the lung, as used in these studies, is sensitive to changes in geometrical distribution of radioactivity within the chest, but the interpretations of the data, as reported here, would not be seriously affected by this factor.

The results obtained with the thoron daughter experiments are probably more representative of particles deposited mainly in the alveoli, and consequently it is still moot whether radon or thoron daughters would be cleared by the ciliary mechanism. It is worth noting that, because the radioactive daughters are fixed onto the surfaces of particles, their distribution in a dust cloud will tend toward the smaller particles, where the surface area is greatest, and these are the ones which would tend to be deposited in the alveoli. This is to be contrasted with the radioactive iron particles, in which the amount of radioactivity is a function of mass rather than of surface area.

There is little doubt that the initial rapid removal of the radioactive iron from the

	PARTICLE SIZE		FIRST DECAY PERIOD (hours)	% CLEARED	SECOND DECAY PERIOD (hours)	% CLEARED
	MMD	GSD				
A. B.	3.5	1.75	2.3	91	---	---
R. A.	3.5	2.13	1.9	86	3.2	95
W. D.	3.5	1.72	2.3	95	---	---
L. A.	4.3	1.72	2.0	75	6.5	88
AVE.			2.1	87		
M. W.	2.3	1.70	4.0	36	31	69
M. E.	2.2	1.64	1.6	47	36	62
H. G.	1.4	1.70	2.4	53	33	75
E. H.	1.9	1.67	2.0	52	32	64
AVE.			2.4	47	33	68

Fig. 8.—Summary data on inhalation of radioactive iron dust.

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lung represented ciliary clearance. Metallic iron is an insoluble material, and the translocation of the radioactivity to the intestine and the lack of appearance in the blood were convincing evidence that the iron was not solubilized to any extent and thus removed from the lung. The speed with which the ciliary mechanism cleanses the bronchial mucosa would appear to make this a very effective means of minimizing radiation damage to the bronchial epithelium. The technique by which this has been demonstrated in humans could no doubt be extended to provide further information on the relationship of particle size to bronchial deposition.

SUMMARY

The effective half-life of thoron daughters in the lung following deposition, together with kaolin particles of mass-median diameter 1.1μ-1.3μ, is about nine hours. This indicates that the pulmonary clearance of radon and thoron daughters under these conditions will not materially reduce the radiation hazard following inhalation.

The early bronchial clearance of radioactive iron particles appears to have two phases: The first clearance period ends in 2 to 4 hours and the second in about 30 hours. The larger the average inhaled particle size, the greater the fraction removed in two to four hours.

U. S. Atomic Energy Commission (Dr. Albert).

693 Madison St. (Dr. Arnett).

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